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See also Report #10020

R 512

Technical Report

WINDOWS FOR EXTERNAL OR INTERNAL HYDROSTATIC PRESSURE VESSELS

Part I — Conical Acrylic Windows Under Short-Term Pressure Application

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NAVAL FACILITIES ENGINEERING COMMAND

U. S. NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

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WINDOWS FOR EXTERNAL OR INTERNAL HYDROSTATIC PRESSURE VESSELS PART I - CONICAL ACRYLIC WINDOWS UNDER SHORT-TERM PRESSURE APPLICATION

Technical Report R-512

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by

J. D. Stachiw and K. O. Gray

ABSTRACT

Conical acrylic windows for fixed ocean-floor structures were placed under short-term loading (pressurization from zero to failure at a fixed rate). The windows, of different thicknesses and different included conical angles, were subjected to various applied pressures, and their subsequent behavior was studied.

Acrylic windows, in the form of truncated cones with included angles of 30°, 60°, 90°, 120°, and 150°, were tested to destruction at ambient room temperature by applying hydrostatic pressure to the base of the truncated cone at a continuous rate of 650 psi/min. The pressure at which the windows failed and the magnitude of displacement through the window mounting at different pressure levels were recorded. The ultimate strength of the conical windows (denoted by the critical pressure at which actual failure occurred) was found to be related both to thickness and included conical angle.

Graphs are presented defining the relationships of critical pressure versus thickness-to-diameter ratio, and pressure versus magnitude of displacement for the windows.

Nondimensional scaling factors for critical pressure and displacement applicable to large-diameter windows are discussed and presented in graphic form.

This initial study produced design criteria for conical acrylic windows for any ocean depth under conditions of short-term loading. These criteria may be applied to windows in either an internal pressure vessel used to contain high pressures, and thus simulate the ocean environment, or an external one used to resist high pressures, such as deep submergence structures in the ocean.

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INTRODUCTION

The Naval Facilities Engineering Command* is responsible for the construction and maintenance of underwater structures attached to the ocean floor. Such structures may include instrumented or manned underwater surveillance or observation posts that will rely, at least in part, on visual observation and the transmitting and receiving of electromagnetic radiation through "non-opaque" hull areas for the performance of their mission. Windows of certain types have been employed for these purposes on research submarines, and have been found to be of practical value especially for visual and sonic (sonar) observation in hydrospace. Similar windows will be utilized on permanent ocean floor installations. The published data on the strength of underwater optical-viewing windows used on submarines is very meager,[1,2,3] and formulas for its calculation are lacking. Furthermore, the operational requirements of permanent underwater installations are sufficiently different from those of submarines to make most of the existing data inapplicable to the deep submergence structures. For these reasons, a study has been undertaken at the Deep Ocean Laboratory of the Naval Civil Engineering Laboratory (NCEL) to generate information for the design of feasible underwater windows. This information, besides satisfying the primary underwater window design requirements, will also prove valuable in the design and operation of windows in internal pressure vessels used for simulation of deep ocean environments.

The performance of underwater windows is influenced by such major factors as the duration of loading or application of pressure; temperature; the thickness, shape, and type of the window material; and the number of pressure cycles involved. Since all these variables must be considered in combination, the whole investigation must proceed in phases, with the factors evaluated in one combination at a time. The phase of study described in this report was planned to determine the relationship between the shape, thickness, and critical pressure of truncated-cone-shaped acrylic plastic windows under short-term loading at room temperature.

BACKGROUND INFORMATION

Windows for underwater applications where high pressures are encountered have been of conical shape since the beginning of deep submergence research. The first scientist to explore this field, Auguste Piccard,[1] not only introduced the conical window shape but also the use of acrylic plastic for windows in deep submergence structures. The conical shape was chosen because of its wide field of vision, as well as its wedging and self-sealing behavior under high pressure. Acrylic plastic, introduced for the underwater application by Professor Piccard in 1939, is still the primary material used for underwater high-pressure windows because of its low cost, wide availability, and excellent optical properties. It is readily bonded, permitting windows of any thickness to be built up by lamination of sheets, and is impact-resistant enough to render unnecessary additional protective covers except for windows employed on combat missions. The long, excellent performance record of acrylic plastic for underwater windows prompted the decision to investigate it first, ahead of other, recently developed optically transparent materials.

Acrylic plastic, like most plastics, deforms with time under sustained loading. For this reason, an acrylic window subjected to sustained pressure loading will ultimately fail at a much lower pressure than if it were pressurized rapidly till failure occurs. Thus, the pressure rating of a window is affected by the duration of load application. In addition, if the window is subjected to more than one pressure cycle of a given duration, its pressure rating will change accordingly. Therefore, to obtain complete design information for acrylic windows, it is necessary to subject them to different types of loadings. However, a standard must be established to which strengths can be compared. Since this has not been done in the course of underwater window investigation to date, a fundamental purpose of the initial phase

*Formerly Bureau of Yards and Docks.

of the present study was to set such a standard. The one selected around which to compile basic data was the failure of windows under short-term pressure application at an ambient temperature in the approximate range of 60° to 70°F. The short-term loading, which denotes not a specific time but pressurization from zero to failure (or critical pressure) at a fixed rate, here was to be applied at the rate of 650 psi/min.

Since the compressive and tensile strength of acrylic material decreases with an increase in temperature, it was considered wise to conduct experiments at prevailing room temperature of 60° to 70°F, for this would be a more severe test than if the pressurizing medium, water, were around 40°F, the temperature of most ocean depths. Also, this temperature range would facilitate the use of conical acrylic windows in internal pressure vessels, where the water employed is likely to be at room temperature.

DESIGN OF EXPERIMENT

The experimental study had two objectives: to determine the short-term pressure strength of a series of windows of different conical angles and thicknesses, and to provide experimental data for future analytical studies dealing with the strength of such windows. To implement the latter objective, the windows were designed not only with a 90° included conical angle, the one customarily used in all present underwater deep submergence windows, but also with 30°, 60°, 120° and 150° included angles. It was felt that by varying the angle from 30° to 150°, sufficient perturbation of the angle parameter was introduced into the experiment to permit the evaluation of its influence on window strength. The thickness-to-diameter (t/D) ratio was varied for the same reason. This ratio is a single, computationally useful nondimensional term combining the two other parameters besides cone angle which determine the critical pressure of conical windows: the thickness, t, of the truncated cone, and the minor diameter, D, of the cone. Sufficient perturbation was assured for the thickness-to-diameter ratio by varying it from 0.125 to 1.0. (Although the t/D ratios are herein expressed in decimal form, sometimes to three places, these values are actually the decimal equivalents of nominal fractional values.)

To obtain true experimental response from the windows whose t/D ratios and conical angles were varied, special effort was made to hold both the temperature and the rate of pressurization constant. Furthermore, the window material and metallic flanges for mounting test specimens were kept the same for each series of experiments, in order to prevent excessive variations in both window material strength and flange rigidity.

A summary of the experiment, reflecting the various categories of the complete test data found in Appendix G, is presented in Table 1.

Table 1. Summary of Experimental Work

Window Diameter 1/ (in.)	Mounting Flange Type	Included Conical Angle (deg)	t/D Ratio (Nominal)	Remarks
1	I	30, 60, 90, 120, 150	0.125, 0.25, 0.375, 0.5, 0.625, 0.75, 0.875, 1.0	Short-term critical pressure and displacement tests
1	I	30	0.5	Low-temperature-effect tests
1	II	30	1.0	Type II flange effect tests
2	I	30	0.125, 0.25, 0.5	Window t/D ratio scaling factor validation tests
4-1/2	I	60	0.125, 0.25, 0.5	Window t/D ratio scaling factor validation tests
8	I	90	0.5	Window t/D ratio scaling factor validation tests

1/ Minor diameter of the truncated acrylic cone.

Window Test Specimens

The conical window test specimens (Figure 1) were machined from acrylic plates and sheets only. The material used was commercial quality Grade G Plexiglas, the physical properties of which are described in Appendix A. This off-the-shelf acrylic material was chosen with the designer in mind, permitting him to specify and easily procure fairly inexpensive stock for his own experimentation or use based on data presented herein.

Since the windows were machined from commercially available sheets and plates of acrylic material, small variations were anticipated in their mechanical properties. Preliminary experiments indicated this variation in strength, together with variations in conical angle and thickness resulting from the necessary machining tolerances, caused considerable scatter of experimental values. Although such a scatter increased the experimental task, certain advantages result for the potential designer. From the range of scatter of experimentally derived critical pressures, the designer can determine what deviations of window strength may be expected when ordinary machine shop tolerances are used on Grade G Plexiglas material received from various manufacturers. Knowing what deviations to expect from the average window strengths given in this report, he will then be able to introduce an appropriate factor of safety.

Since it may often be difficult or economically impractical to provide future submarines, permanent underwater installations, or pressure vessels requiring cone-shaped acrylic windows with custom-fitted, lapped-in-place originals or replacements, this study has relied exclusively on mass-produced, interchangeable specimens. None of the windows received any further shaping or lapping in place following fabrication in the NCEL machine shop. Spot checks of the as-machined windows indicated dimensions were less than ±30 minutes off from specified nominal angle, and ±0.020 inch from the specified nominal thickness. The sealing surfaces of the windows were machined to a 32 rms finish, while the parallel viewing surfaces were polished to an optical finish.

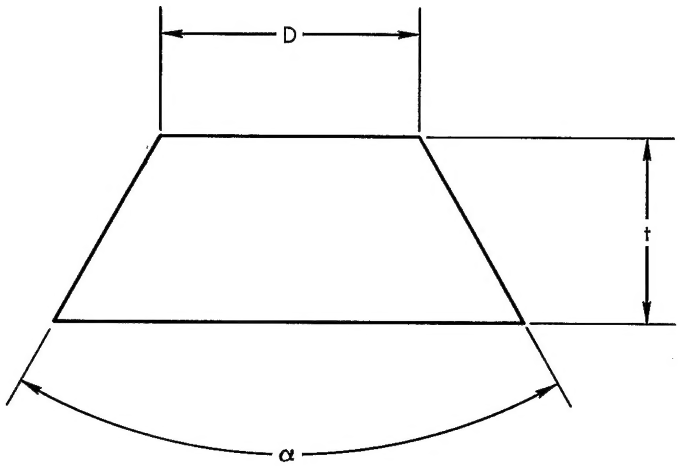
Window Specimen Holders

The test specimens were mounted in metallic flanges designed to fit into the end closure of the pressure vessel (Figure 2). The pressure vessel employed for this study was the Mk-I modification of 16-inch Naval gun shells,[4] a convenient, medium-size vessel with a useful inside diameter of 9 inches. (This diameter determined the choice of the minor diameter of 1 inch for the basic series of window test specimens, since the major diameter of the acrylic window specimens tested could reach 6-1/4 inches, and in the case of validation tests with larger diameter windows, 8 inches.)

The mounting flanges, machined from mild steel, were of sufficient thickness to withstand all but minor deformation during application of hydrostatic pressure to the window specimens. In addition to the dimensional stability offered by the rigidity of the comparatively massive flange construction, the hydrostatic loading caused by surrounding fluid under pressure also acted on the flange to minimize its expansion from the wedging action of the conical window. It can, therefore, be postulated that for all practical purposes the window flanges were rigid, and only the acrylic windows were deformed during the tests.

Mounting flanges with conical cavities of different angle sizes were employed to accommodate the range of 30° to 150° included angles of the conical window specimens. A cylindrical cavity of varying length extended beyond the conical cavity of the mounting flange, to accommodate the displaced (extruded or deflected) portion of the window resulting from pressure action. (See Figure 3.) Flanges were of two types, DOL (Deep Ocean Laboratory) Type I and DOL Type II, with a difference in configuration related chiefly to the radial restraint provided by the cavity receiving the displaced portion of the window and explained in the paragraphs which follow. In this study, the DOL Type II configuration flange was used only in a small number of tests, for exploratory purposes.

To standardize the displacement aspect of testing, all windows were machined to position the low-pressure (minor-diameter) surface flush with the small end of the conical cavity in the mounting flange. Thus, as the thickness of the windows tested varied, the high-pressure face (the one exposed to the hydrostatic pressure) extended to different elevations in the flange conical cavity. As the window moved axially under hydrostatic pressure, portions of it would protrude into the adjoining cylindrical cavity, and would not be further subjected to wedging action by the flange.



Included Conical Angle, α 1/ (deg)	Window Diam, D (in.) 2/	t/D Ratio (Nominal)							
		0.125	0.25	0.375	0.5	0.625	0.75	0.875	1.0
		Nominal Thickness, t (in.) 3/							
30	1	1/8	1/4	3/8	1/2	5/8	3/4	7/8	1.0
60	1	1/8	1/4	3/8	1/2	5/8	-	-	-
90	1	1/8	1/4	3/8	1/2	5/8	-	-	-
120	1	1/8	1/4	3/8	1/2	5/8	-	-	-
150	1	1/8	1/4	3/8	1/2	5/8	-	-	-
30	2	1/4	1/2	-	1	-	-	-	-
60	4-1/2	9/16	1-1/8	-	2-1/4	-	-	-	-
90	8	-	-	-	4	-	-	-	-

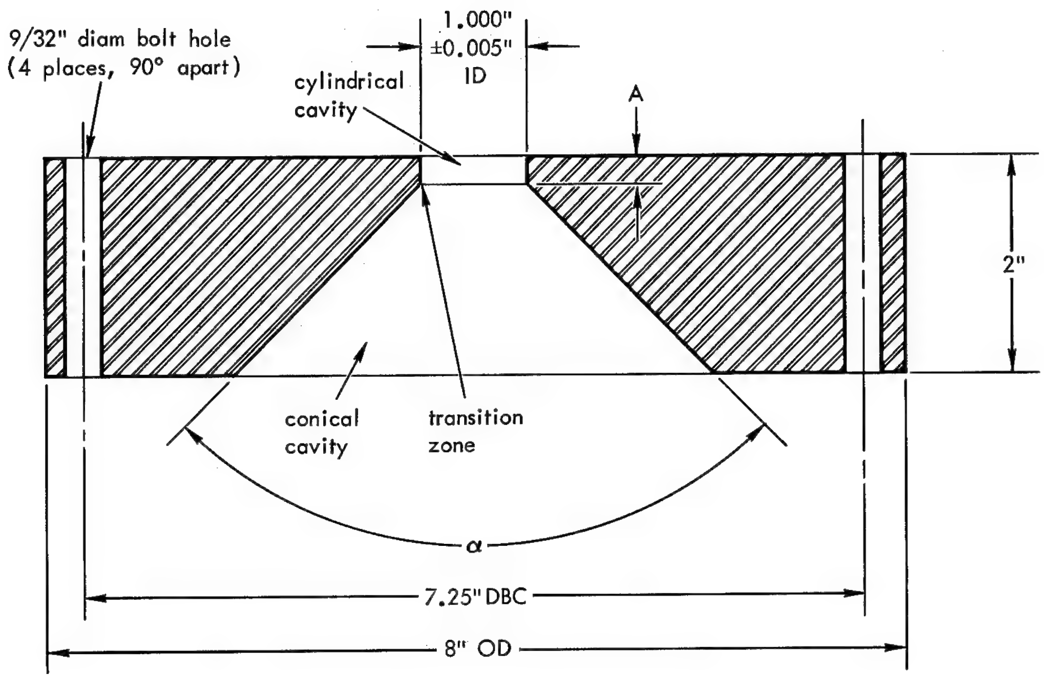
1/ Dimensional tolerance of ±30 minutes.

2/ Diameter of low-pressure face (minor diameter), with tolerance of ± 0.005 inch.

3/ Commercial stock size, with tolerance of ±10%.

Figure 1. Types of conical acrylic window test specimens.

Figure 2. Steel mounting flange for conical acrylic windows attached to end closure of Mk-I pressure vessel.



Included Conical Angle, α 1/ (deg)	Cylindrical Cavity Length, A (in.)
30	1/4
60	1/4
90	1/4
120	1/2
150	1-1/4

1/ Dimensional tolerance of ±30 minutes.

Figure 3. Steel mounting flanges, DOL Type I configuration, for 1-inch-diameter conical acrylic window test specimens.

Exploratory work (Table G-11, Appendix G) indicated that continued radial support for the displaced portion of the window has a definite relationship to the window critical pressure. Therefore, each test mounting flange, though its cylindrical cavity in many cases had a length of only 0.25 inch, was backed by a flange adapter (Figure 4) with a cylindrical cavity always matching the minor diameter of the mounting flange cavity. In this way, regardless of how much a window extruded, its extruded portion was always radially restrained by a cylindrical wall, either of the flange or of the adapter. Such arrangement standardized the test conditions for window specimens whatever their thickness, conical angle, diameter, or amount of displacement under testing. The type of flange configuration assuring the displaced portion of support, whatever its length, was designated DOL Type I, and the one not providing such support, DOL Type II. (See Appendix F.) In the latter configuration, the cavity for receiving the displaced portion of the window was not cylindrical but flared sharply, and was not extended by use of a flange adapter.

Instrumentation

The instrumentation consisted of a thermometer, a pressure gage, and a displacement measuring device. The thermometer was used to measure the temperature of the water in contact with the window in the vessel; the pressure gage, the pressure of the water in the vessel; and the displacement measuring device, within 0.001 inch, the displacement of the center of the window low-pressure face as it extruded or deflected into the cylindrical cavity of the mounting. Since the displacement measuring device (Figures 5 and 6) was mechanical, no problems were encountered in zeroing or balancing it. Although more sophisticated instrumentation employing electric resistance strain gages[2] or photoelastic techniques[3] could have been used, its potential contribution in the determination of ultimate short-term window strength was deemed insufficient to warrant consideration.

TEST PROCEDURE

The window mounting flange with the appropriate conical opening was placed on the flange adapter (Figure 4) and bolted in position. The window, to which the displacement indicator wire was already fastened by means of a small acrylic anchor piece cemented onto its low-pressure face, was liberally coated with silicone grease and inserted into the mounting flange. No retaining device was necessary, as the grease exerted enough adhesion to keep the window from falling out. Next, the mounting assembly was inserted into the end closure of the pressure vessel and locked in place. The 0.010-inch-thick steel wire connected to the window low-pressure face was then fastened to a 1-pound weight. With the wire positioned over pulleys that centered one wire end over the window and the other over a dial indicator, the weight was placed on the dial indicator rod, depressing it slightly (Figure 5). During the experiment, the weight was kept from shifting on the dial indicator rod by a plastic weight guide tube and a recess on the bottom of the weight into which the indicator rod fitted. The test setup with the displacement measuring device in position is shown in Figure 6.

To permit pressurization of the vessel, three entries were provided in the top of the vessel end closure. One was used to admit the pressurizing fluid to the vessel, one for sensing the pressure, and one to remove entrapped air and to relieve the pressure in the vessel on completion of the test. The pressure inside the vessel was monitored at all times with a 16-inch-diameter Bourdon tube-type pressure gage connected to a fitting in the end closure with 1/16-inch-outside-diameter tubing. The use of such small tubing was instrumental in reducing the severity of the hydraulic shock to the mechanism of the gage at the moment of window failure, when the pressure in the vessel was reduced from as high as 30,000 psi to 0 psi in less than 1 second. The pressurization of the vessel was accomplished by means of two air-driven pumps with a maximum pressurization capability of 30,000 psi (Figure 7).

Although different rates of pressurization were feasible, a pumping rate of 650 ±100 psi/min was selected as a standard. The temperature of the pressurizing medium (fresh water) and of the vessel was maintained in the general range of 60° to 70°F, although for some selected tests it was reduced to a range of 35° to 40°F. The temperature readings were recorded before and after window failure to obtain an average.

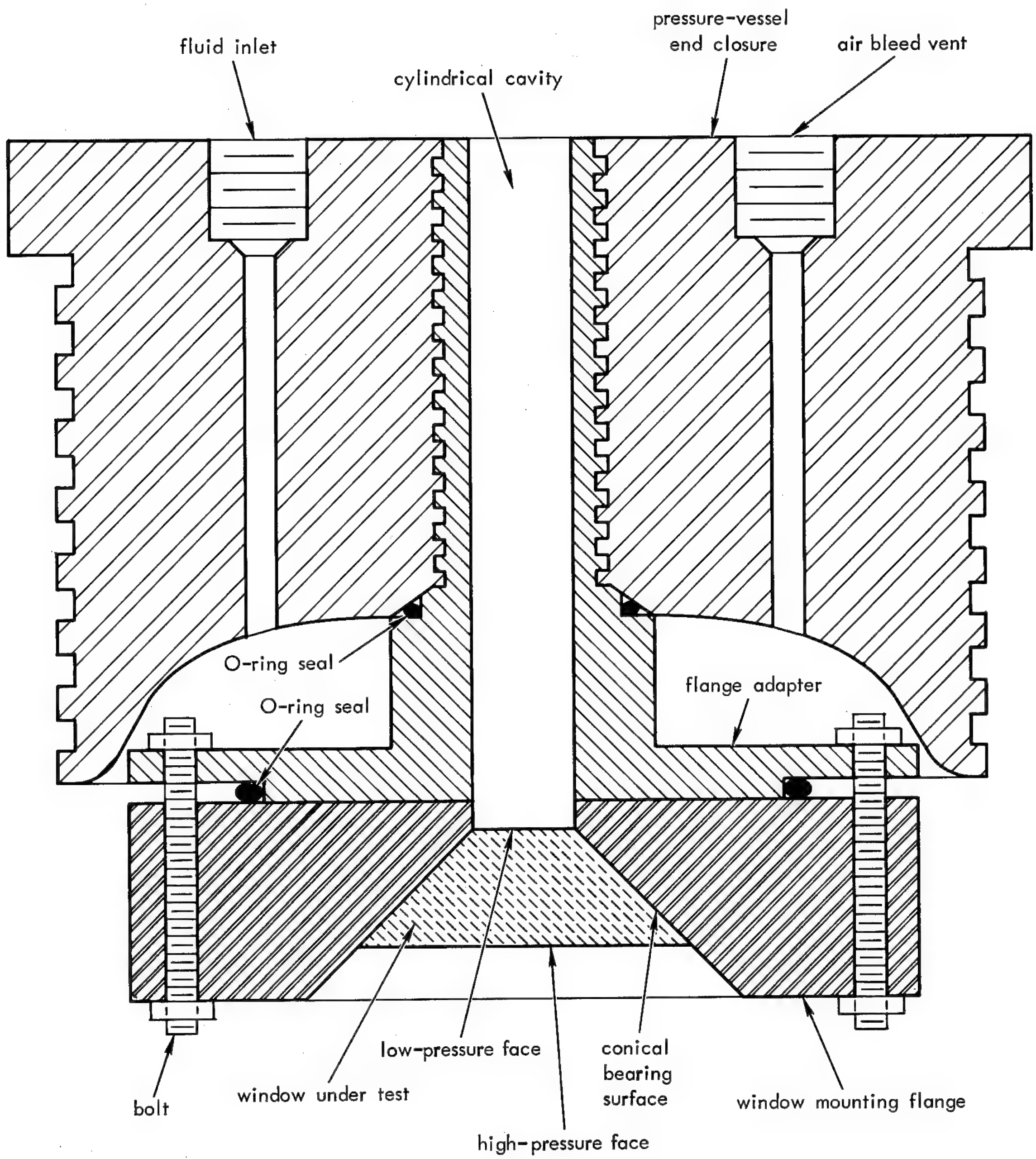


Figure 4. Flange adapter attached to DOL Type I mounting flange, with mounting assembly positioned in end closure of pressure vessel.

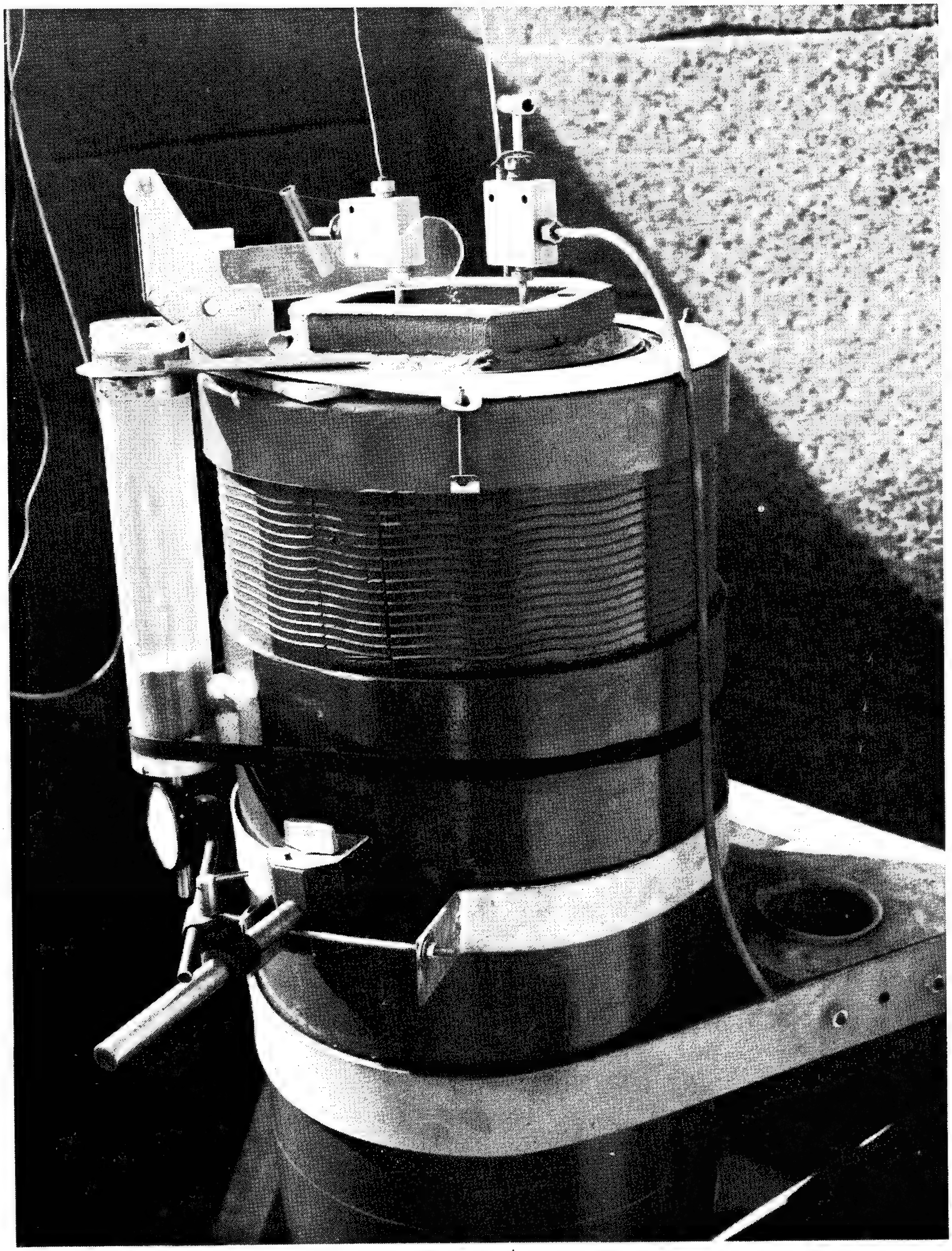


Figure 5. Window displacement measuring device.

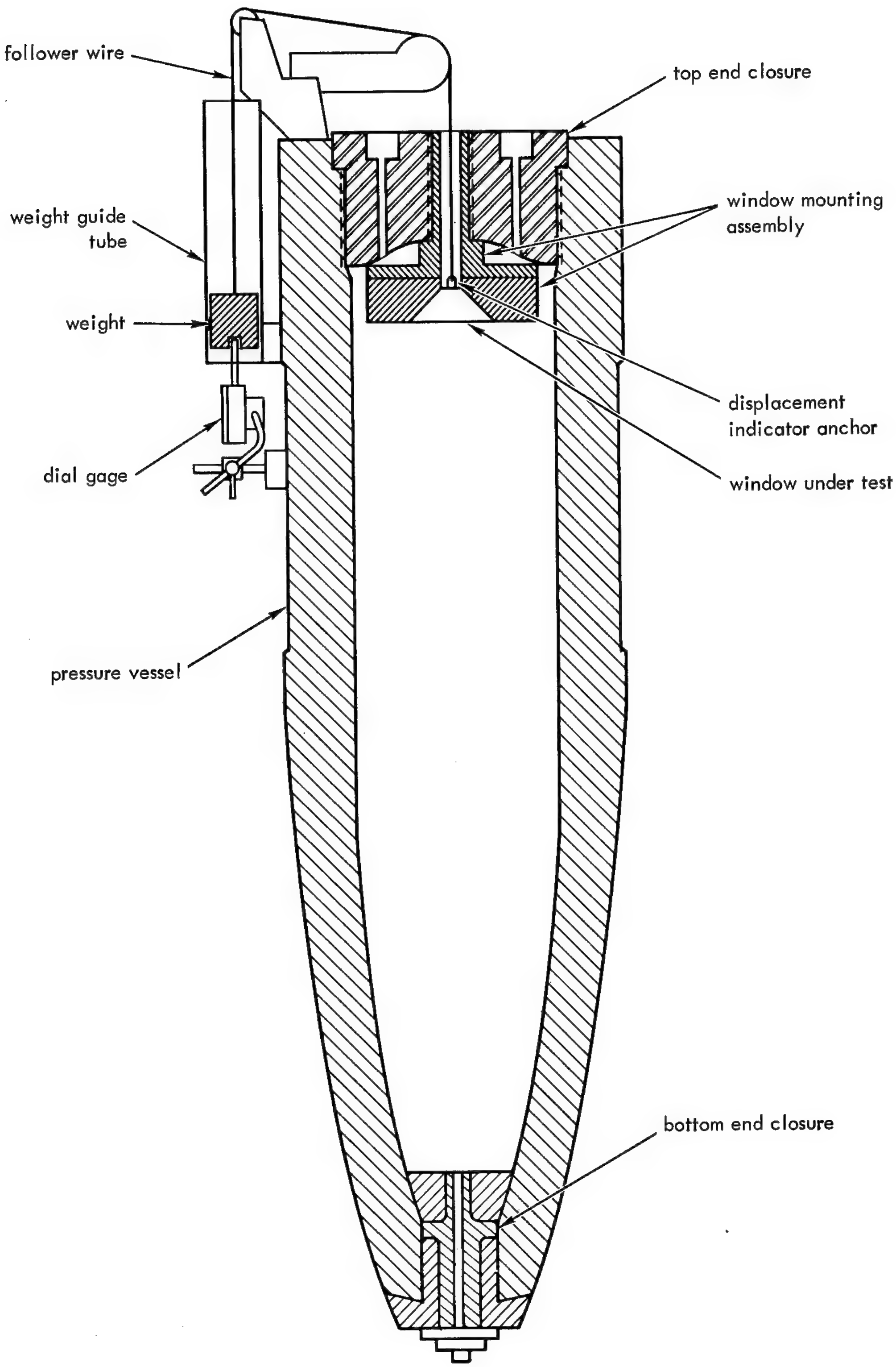


Figure 6. Schematic of window test assembly, with window displacement measuring device in position.

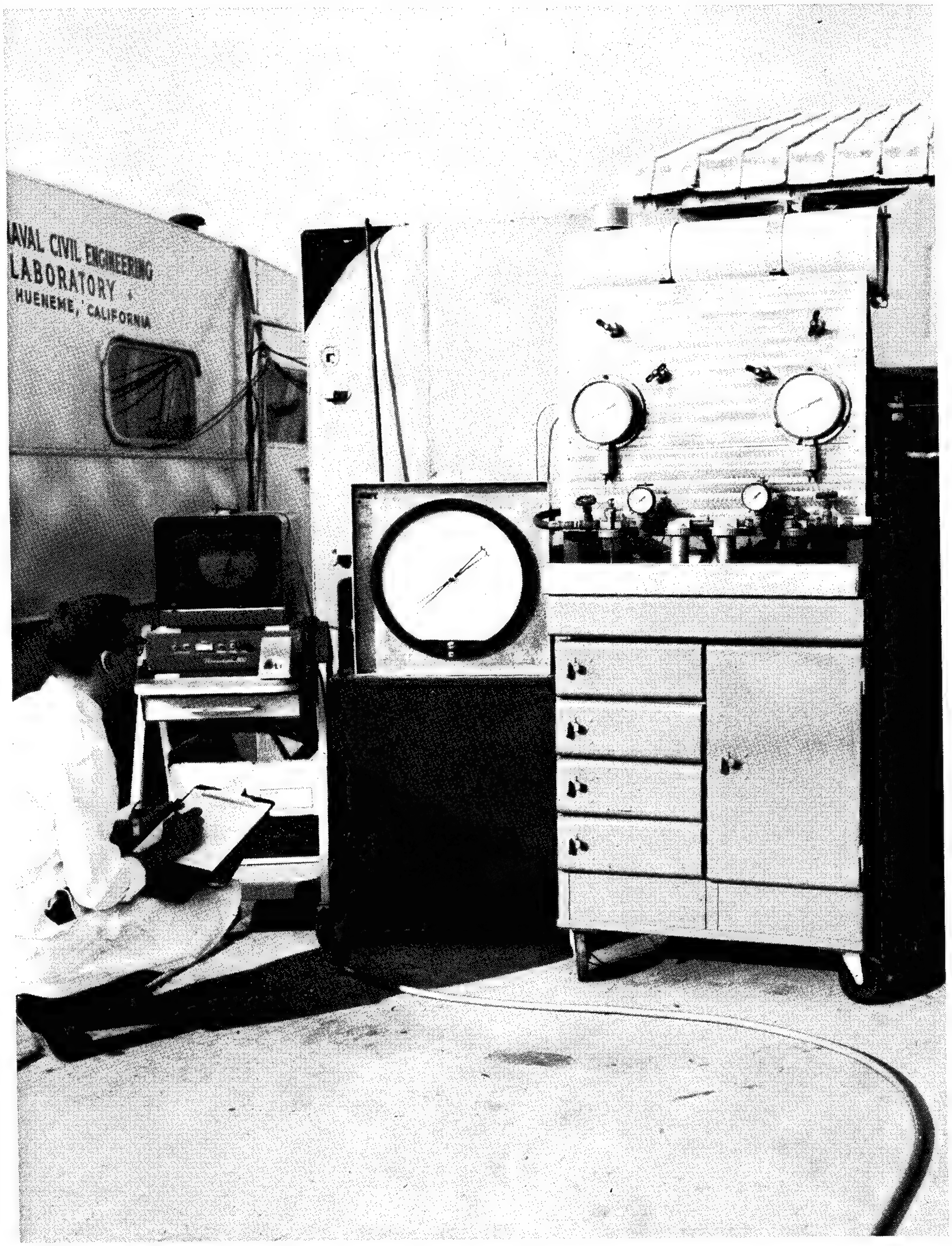


Figure 7. High-pressure pumping unit, precision pressure gage (center), and television monitor used in test procedure.

Once the pressurization process was begun, it was continued until the window failed. Displacement readings were recorded at 1, 000-psi intervals without interruption of the pressurizing. Both the pressurization and the recording of displacement data were continuous until window failure occurred with an explosive release of compressed water and fragments of window. Water and fragments were ejected high into the air through the opening in the end closure. To protect the operator of the pressurizing system from possible failure of the vessel, he as well as the monitoring equipment were separated from the test area by a massive concrete block (Figure 8). The dial indicator readings were observed by means of a closed-circuit television system (Figure 9).

EXPERIMENTAL DATA

All the windows which were tested to destruction failed explosively. There was, however, a distinct difference in the mode of failure among the windows, depending on their t/D ratio and included angle. Discussion of the modes of failure is presented in Appendix B.

Scatter of Data

Experimental data consisting of critical pressures at which window failures occurred and magnitudes of displacement at different pressures varied from window to window, even though the windows were of the same nominal dimensions. To obtain a representative value of the experimental parameters, five or more windows of each nominal thickness used were tested for each t/D ratio, and their critical pressures and displacements averaged. This procedure was repeated for each conical angle considered. Since eight nominal t/D ratios and five conical angles were investigated, around 200 experiments were performed and the data from them recorded.

Because the average of any number of experimental readings at a given t/D ratio does not convey adequately the scatter of individual readings, both the minimum and the maximum of each experimental parameter range were also recorded for each t/D ratio. In general, it can be stated that the range of scatter of individual experimental points is less than plus-or-minus 10% of the average value computed for a given t/D ratio and conical angle. Such a magnitude of scatter range is small when one considers that the variation in temperature was of the same magnitude, the thickness of the windows varied within plus-or-minus 0. 020 inch of nominal thickness, and that the angular dimension varied within ±30 minutes of the nominal value.

Size of Sample Group. The size of the sample group was varied and statistical methods were used to verify that five experimental values provided an adequate representation of the experimentally determined variables. The discussion of this study is presented in Appendix C.

Effects of Temperature. Groups of similar specimens were tested at both 35° to 40°F and 67° to 75°F; it was determined that the lower temperature produced a measurable increase in the critical pressure. The discussion of this study is presented in Appendix D.

Subsidiary Experiments

Applicability of 1-Inch-Diameter Window Test Data to Windows of Larger Sizes. Several experiments were conducted with larger windows to determine if the data obtained from tested 1-inch-diameter windows was applicable to larger sizes. It was determined that the t/D ratio (with certain limiting conditions) is a direct scaling factor for critical pressure and that displacement, while not directly scalable, can be estimated reasonably accurately with an appropriate scaling factor. The data and discussion are presented in Appendix E.

Evaluation of Other Window Mounting Flange Configurations. Exploratory experiments were conducted which demonstrated that the configuration of the transition zone between the adjoining cavities of the mounting flange, the conical cavity and the one for accommodating the acrylic displacement, has considerable influence on the short-term critical pressure of the window.

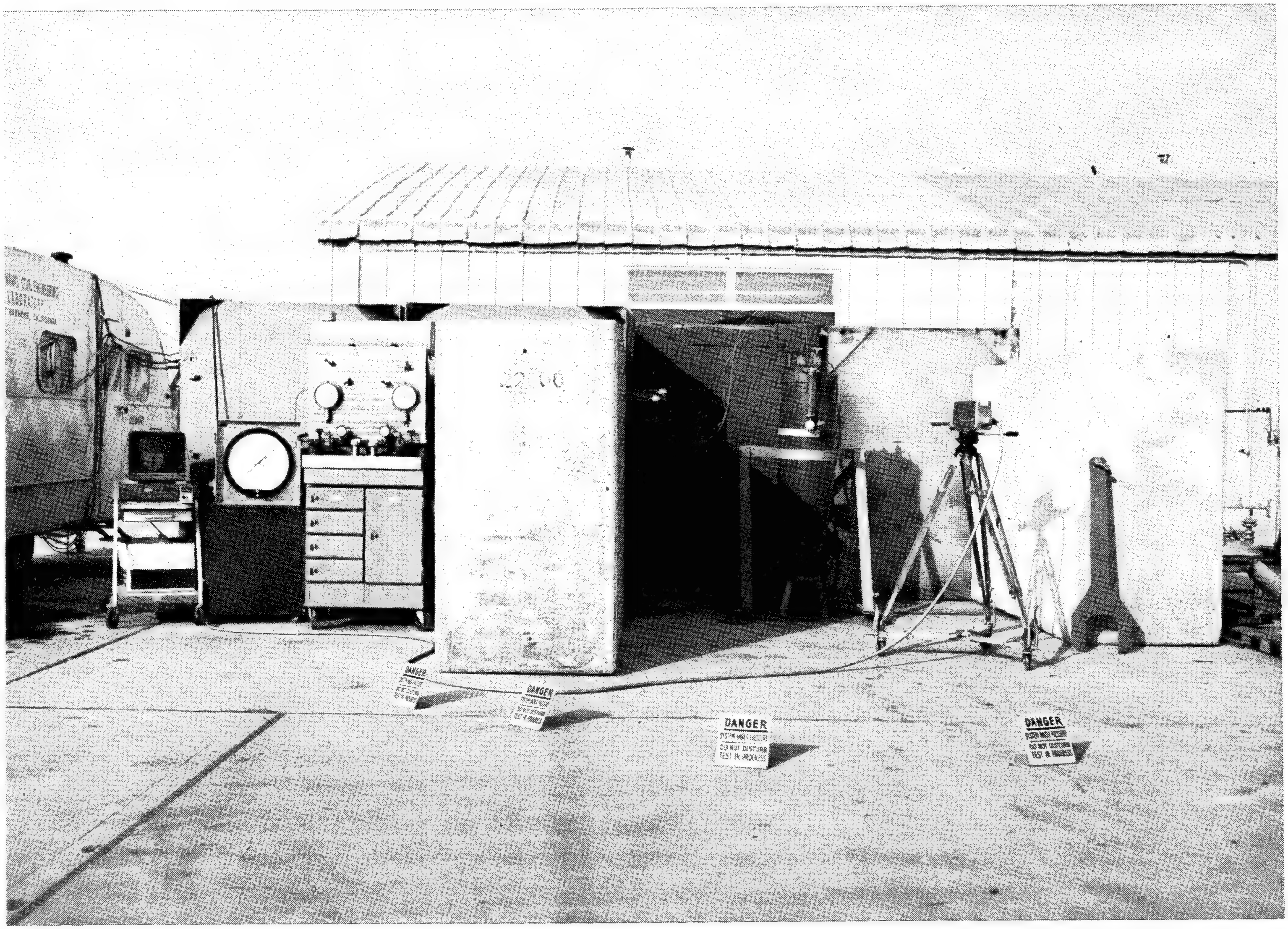


Figure 8. Complete setup for window test program.

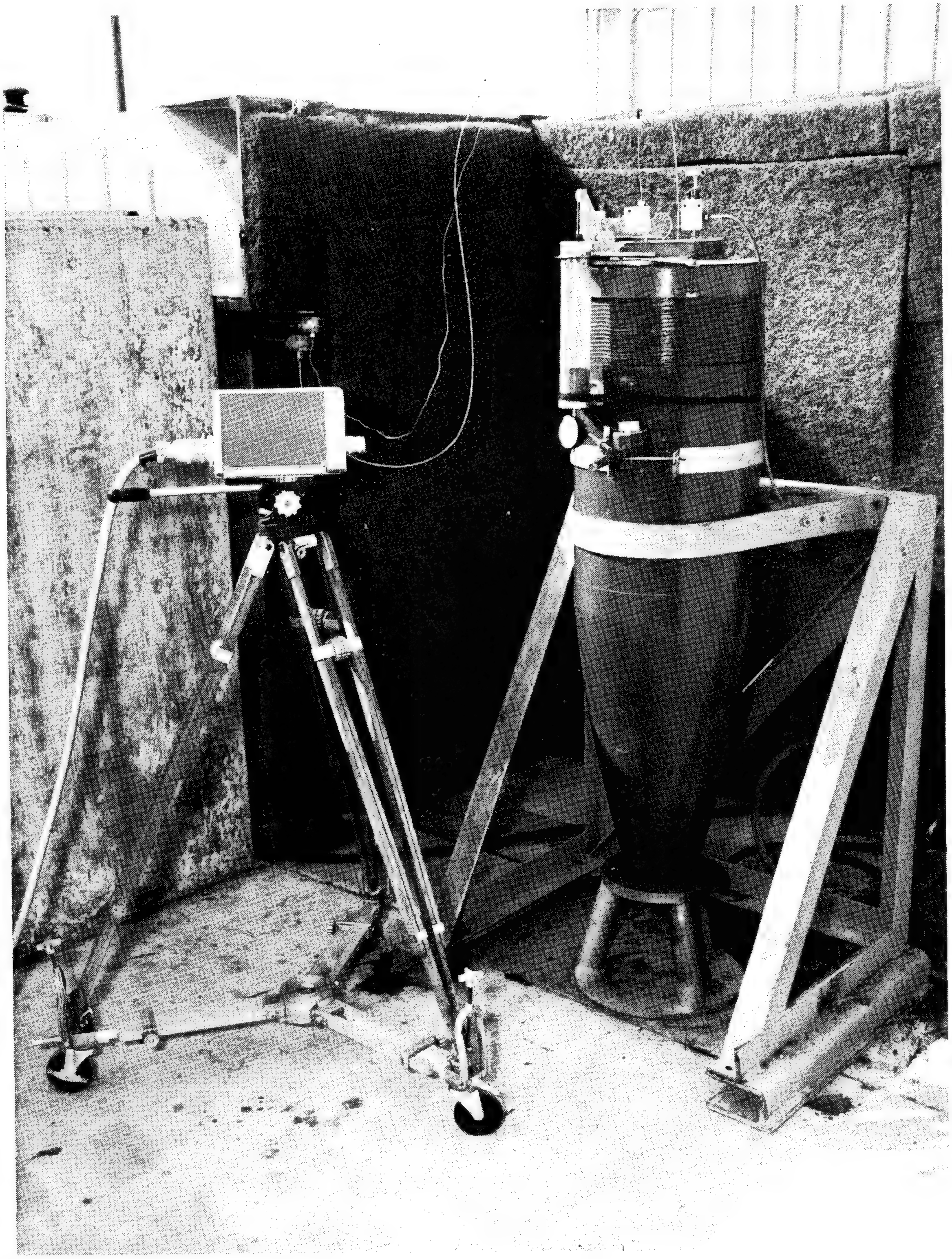


Figure 9. Window displacement measuring system with television camera used to monitor dial gage readings.

One-Inch-Diameter, 30° Conical Windows

Complete data from the testing of 1-inch-diameter, 30° conical windows are presented in Tables G-1 through G-11, Appendix G.

All these windows failed by being ejected from the vessel. In every case the whole window disintegrated into small particles that were carried outside the vessel by the high-velocity stream of water. Inspection of the mounting flange failed to show any pieces of the fractured window adhering to it.

The critical pressure recorded during the testing of the 30° window specimens (Figure 10), when plotted, appear to vary exponentially with t/D ratios, with small variations in the ratio producing large differences in pressure. The displacements of the windows (Figure 11) were large and decidedly nonlinear for all t/D ratios.

One-Inch-Diameter, 60° Conical Windows

Complete data from the testing of 1-inch-diameter, 60° conical windows are presented in Tables G-12 through G-16, Appendix G.

In comparing the critical pressures of the 60° windows (Figure 12) with those of the 30° windows, it became apparent that the 60° type of window was the more pressure-resistant. The differences in critical pressure between windows of the same t/D ratio but different included angle varied with the t/D ratio. The difference was quite small at low t/D ratios, but extremely large at intermediate and high t/D ratios. The high critical pressures of 60° windows were accompanied by smaller displacements (Figure 13) when comparison was made at the same pressure to 30° windows of the same t/D ratio.

One-Inch-Diameter, 90° Conical Windows

Complete data from the testing of 1-inch-diameter, 90° conical windows are presented in Tables G-17 through G-22, Appendix G.

The critical pressures of the 90° windows (Figure 14) were not markedly higher than those of the 60° windows with the same t/D ratio. This showed that the increase in short-term pressure resistance of conical windows, with increase of included angle, was reaching a plateau with the 90° windows, and probably no further gain in pressure resistance was to be achieved by enlarging the included conical angle to 120° or 150°. The displacements of the 90° windows (Figure 15) were observed to be significantly less than those of the 60° windows.

One-Inch-Diameter, 120° Conical Windows

Complete data from the testing of 1-inch-diameter, 120° conical windows are presented in Tables G-23 through G-27, Appendix G.

The critical pressures of these windows (Figure 16) were found to be essentially the same as those of the 90° windows. This seemed to indicate that no further advantage was to be gained in terms of pressure capability by increasing the angle of the windows past 90°.

The displacements of the 120° windows (Figure 17) were observed to be approximately the same as those of 90° windows. Since the displacements were generally smaller than those for the 90° windows, and since the cold-flow cratering (pressure-induced plastic deformation, here a depression, occurring at room temperature) on the high-pressure face of the 120° windows appeared to be less pronounced at the same pressure than for 90° windows, the 120° windows would probably perform better optically at higher pressures than the 90° windows.

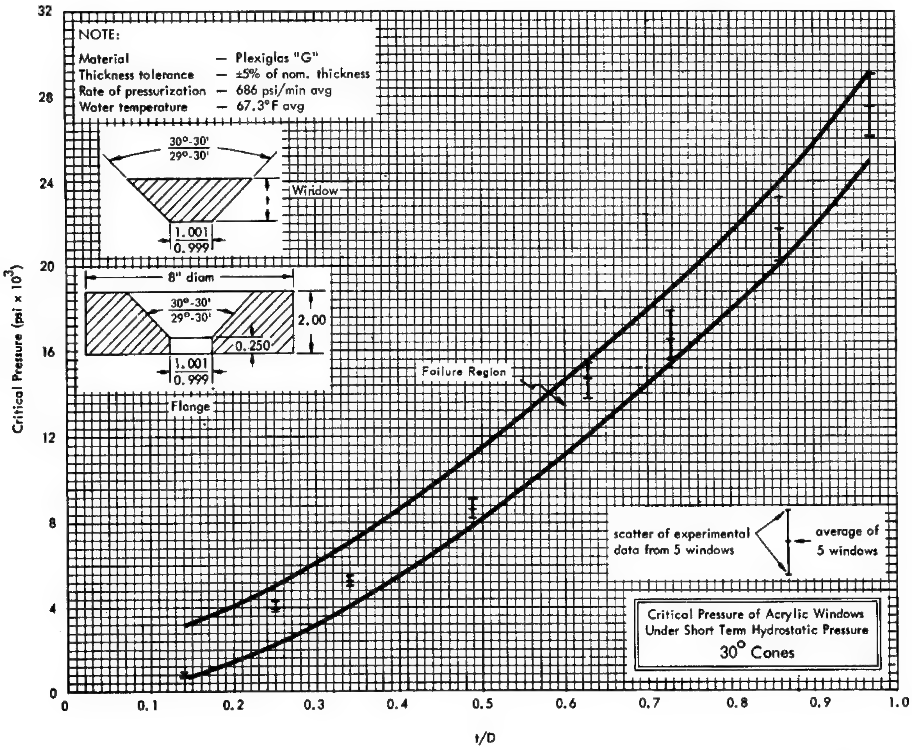


Figure 10. Critical pressures of 1-inch-diameter, 30° conical acrylic windows under short-term hydrostatic pressure.

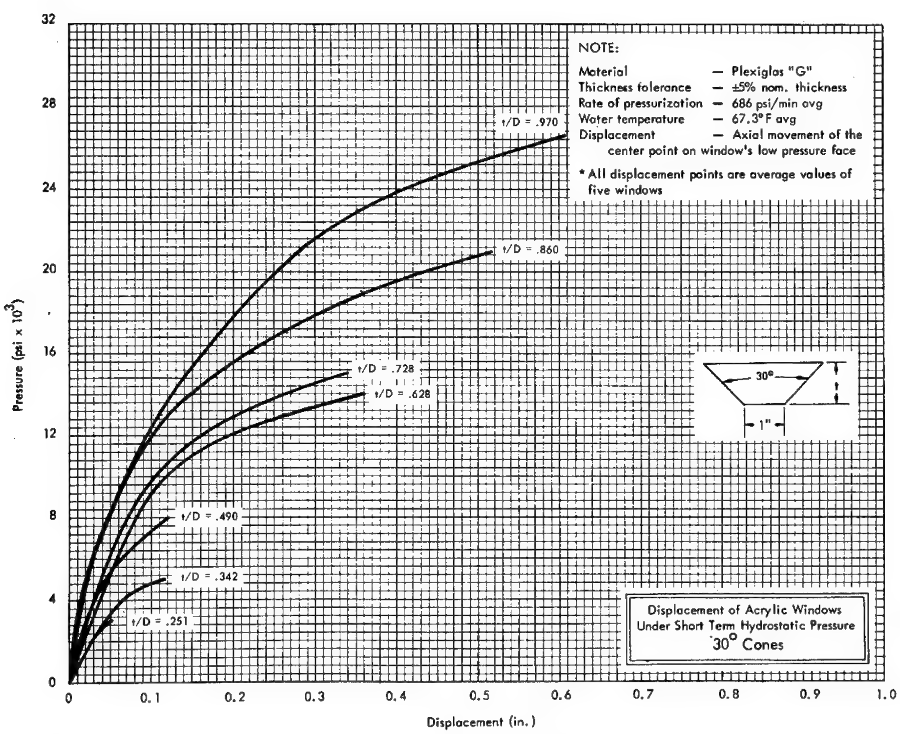


Figure 11. Displacements of 1-inch-diameter, 30° conical acrylic windows under short-term hydrostatic pressure.

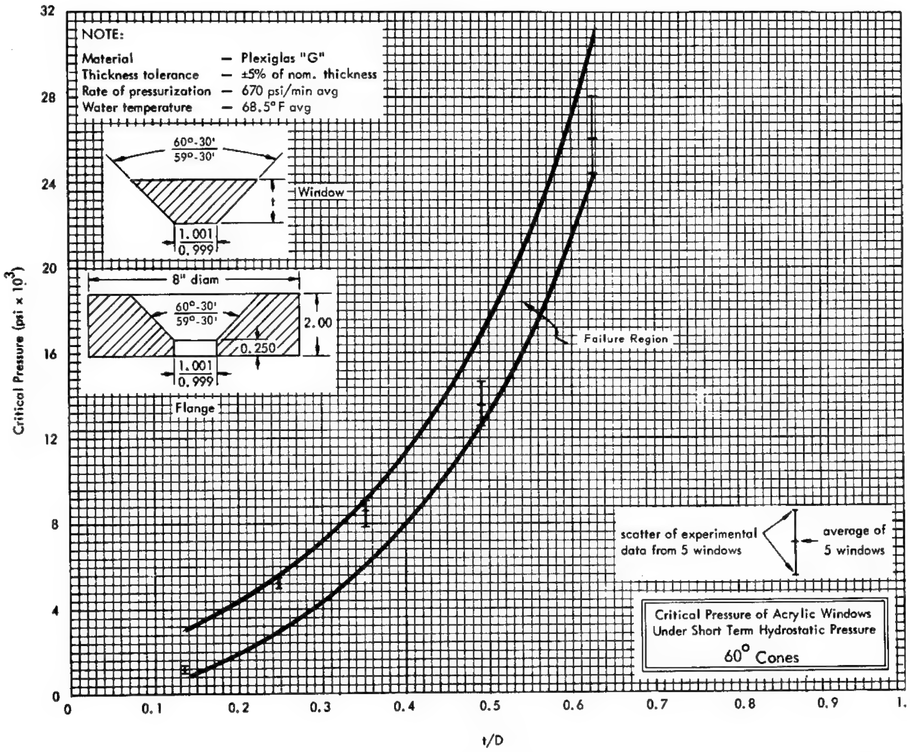


Figure 12. Critical pressures of 1-inch-diameter, 60° conical acrylic windows under short-term hydrostatic pressure.

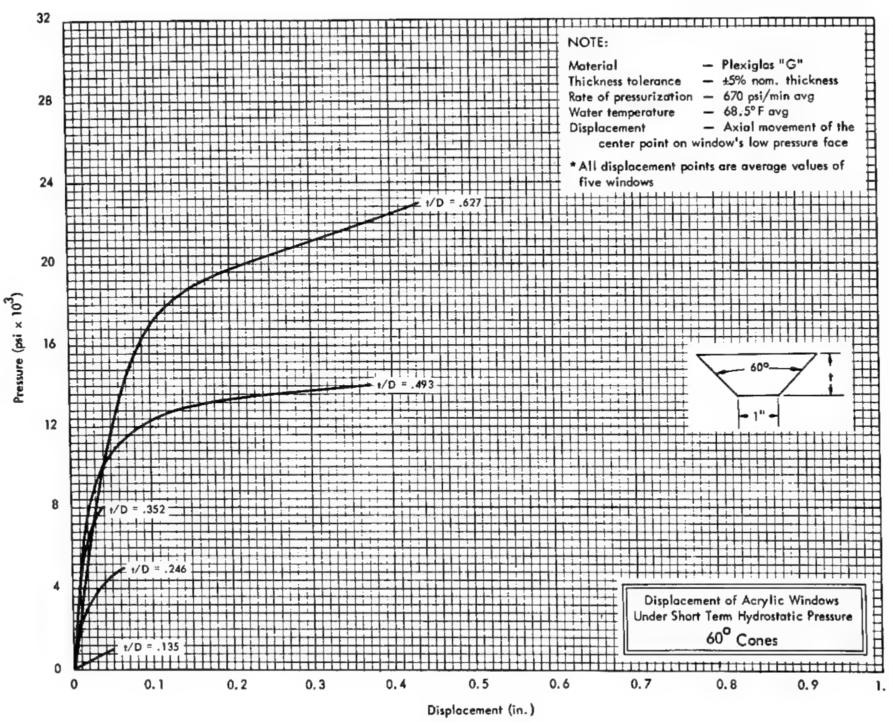


Figure 13. Displacements of 1-inch-diameter, 60° conical acrylic windows under short-term hydrostatic pressure.

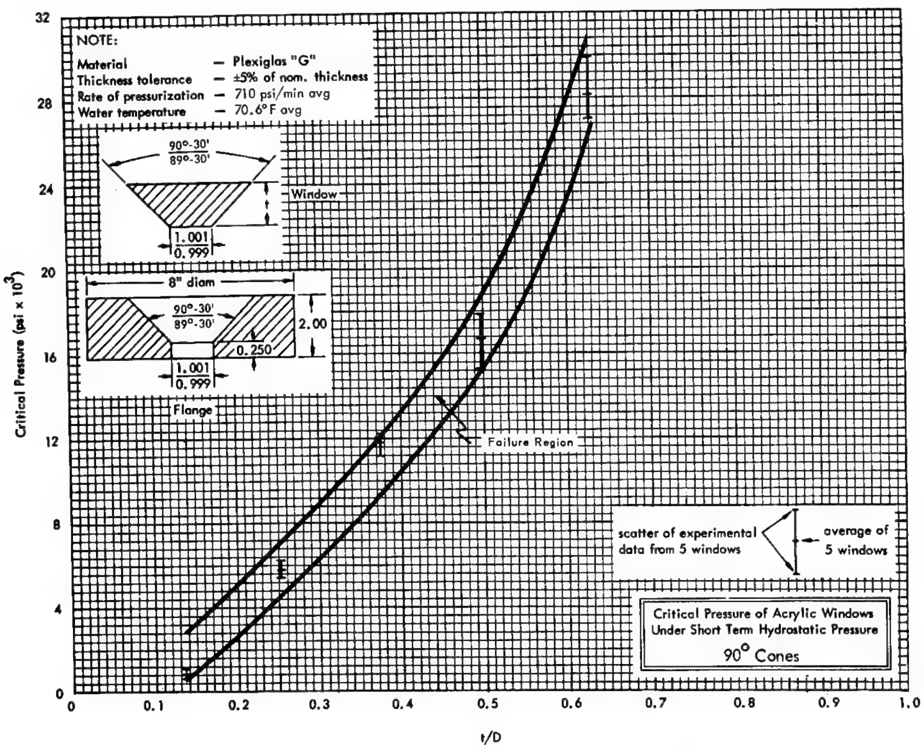


Figure 14. Critical pressures of 1-inch-diameter, 90° conical acrylic windows under short-term hydrostatic pressure.

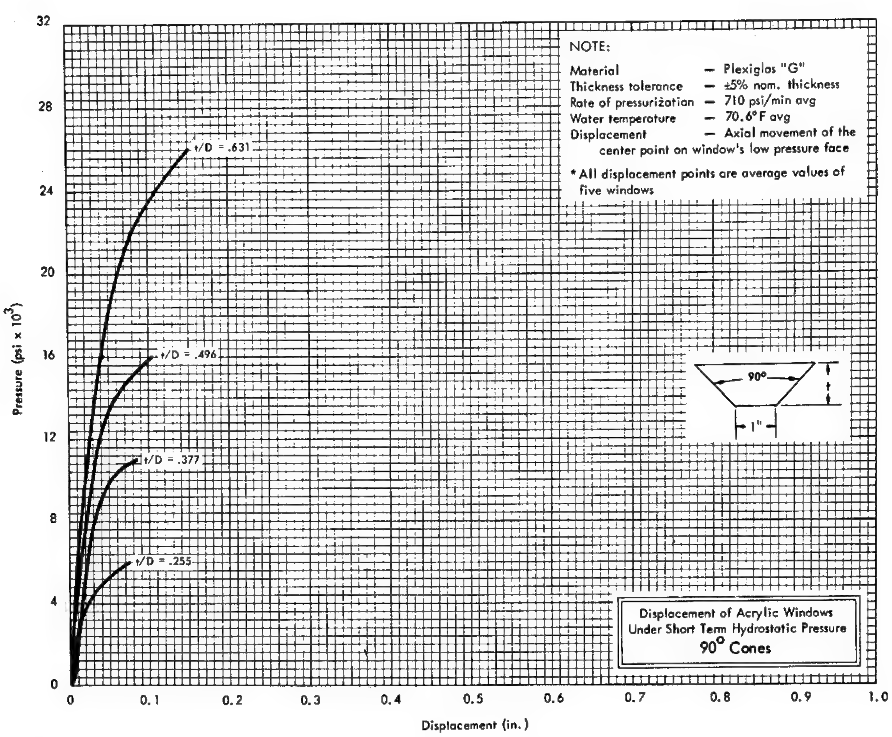


Figure 15. Displacements of 1-inch-diameter, 90° conical acrylic windows under short-term hydrostatic pressure.

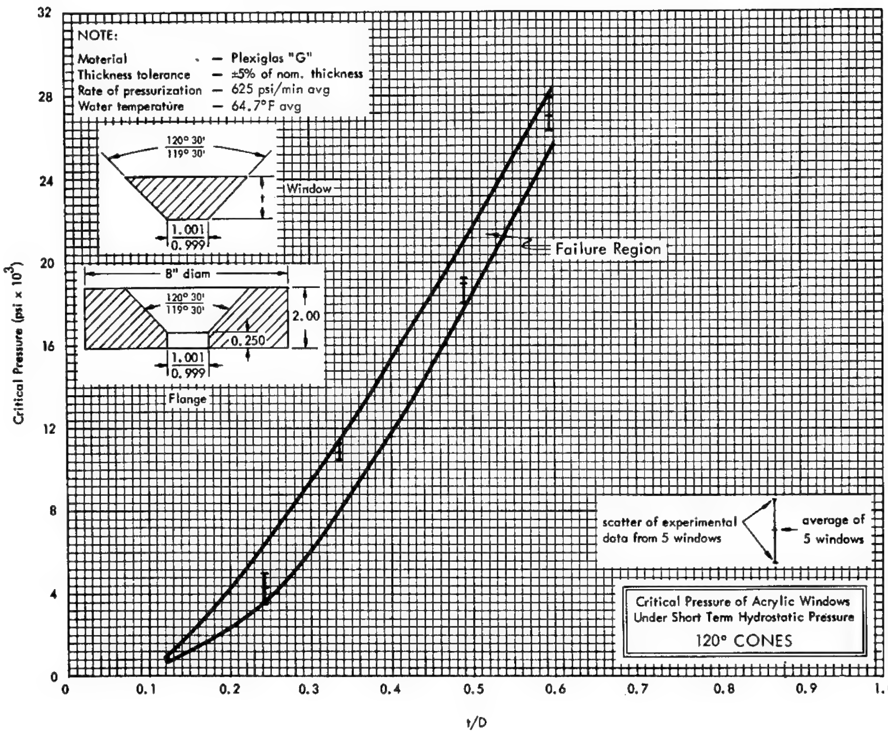


Figure 16. Critical pressures of 1-inch-diameter, 120° conical acrylic windows under short-term hydrostatic pressure.

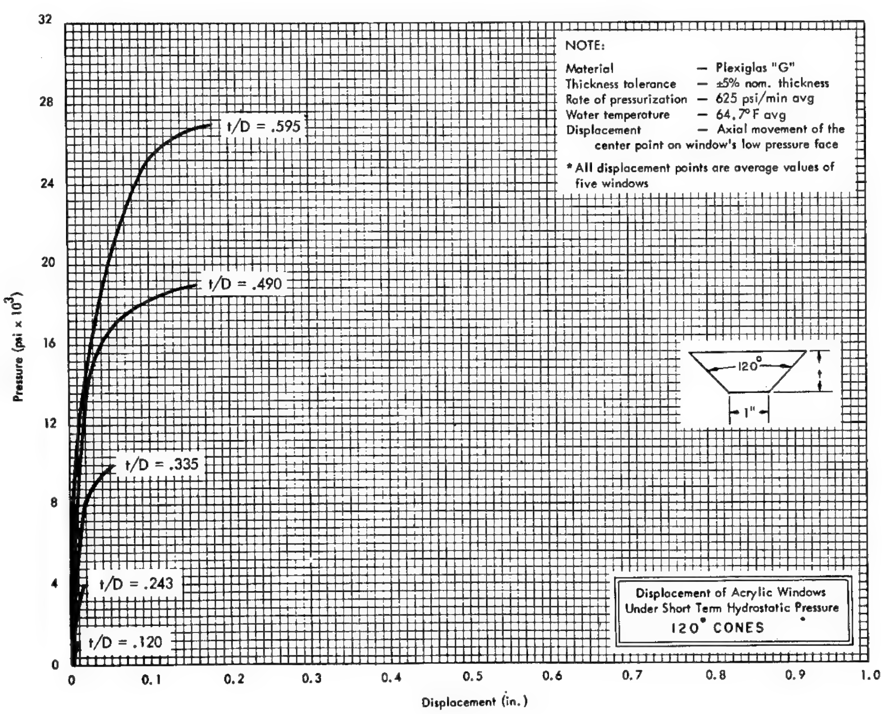


Figure 17. Displacements of 1-inch-diameter, 120° conical acrylic windows under short-term hydrostatic pressure.

One-Inch-Diameter, 150° Conical Windows

Complete data from the testing of 1-inch-diameter, 150° conical windows are presented in Tables G-28 through G-33, Appendix G.

The critical pressures of the 150° conical windows (Figure 18) were in general the same as those of 120° windows, except for 0.375 t/D ratio windows, whose critical pressures were slightly higher. This indicated that, for the most part, no benefit in critical pressure was to be derived by increasing the included angle of the windows above 90° or 120°.

The displacements of the 150° conical windows (Figure 19) were, in general, the same as those of the 120° windows, but noticeably smaller than those of the 90° windows. The shape of the displacement curves shows that very little plastic flow took place in the 150° conical windows prior to their failure at critical pressure, much the same as in the case of the 120° windows.

Two-Inch-Diameter, 30° Conical Windows

Complete data from the testing of 2-inch-diameter, 30° conical windows are presented in Tables G-34 through G-37, Appendix G.

These windows failed at pressures (Figure 20) approximately the same as those of 1-inch-diameter, 30° windows with the same t/D ratio.

The displacements of the 2-inch-diameter windows (Figure 21) were found to be considerably larger than those of the 1-inch-diameter windows with the same t/D ratios. A definite ratio between the magnitudes of displacement for windows of these two diameters could not be derived which would be accurate regardless of t/D ratio. Nevertheless, a 1:2 ratio, representing the ratio between the 1-inch- and 2-inch-diameter windows, can prove useful in estimating the displacement of 2-inch-diameter windows of various t/D ratios from known displacements of 1-inch-diameter windows.

Four-and-One-Half-Inch-Diameter, 60° Conical Windows

Complete data from the testing of 4.5-inch-diameter, 60° conical windows are presented in Tables G-38 through G-40, Appendix G.

The window specimens tested of this type, with t/D ratios of 0.125, 0.25, and 0.5, failed at essentially the same pressures (Figure 22) as the 1-inch-diameter windows with the same t/D ratios. The displacements of the 4.5-inch-diameter windows, however, differed considerably from those of the 1-inch-diameter, 60° windows. When the magnitude of displacement of the 4.5-inch-diameter windows (Figure 23) was compared to that of the 1-inch-diameter windows, it was found to be considerably higher. Although a definite ratio between the magnitudes of displacement for windows with these two diameters could not be derived which would be accurate regardless of the t/D ratio, it appears that a t/D ratio of 1:4.5 is a good approximation. This figure would indicate that the ratio of displacement magnitude for 1-inch- and 4.5-inch-diameter windows is probably the same as that of the two window diameters.

Eight-Inch-Diameter, 90° Conical Windows

The short-term hydrostatic testing with an 8-inch-diameter, 90° conical window (Figures 24 and 25) was conducted under the same experimental conditions as those for 1-inch-diameter, 90° windows, except that an 18-inch-inside-diameter pressure vessel (Figure 25) was used for pressurization. Only the 0.5 t/D ratio was investigated, and its critical pressure compared to that of the 1-inch-diameter conical windows with a 0.5 t/D ratio.

The critical pressure (Figure 26) of the 8-inch-diameter, 90° window was found to be essentially the same as the critical pressure of the 1-inch-diameter, 90° window with corresponding t/D ratio.

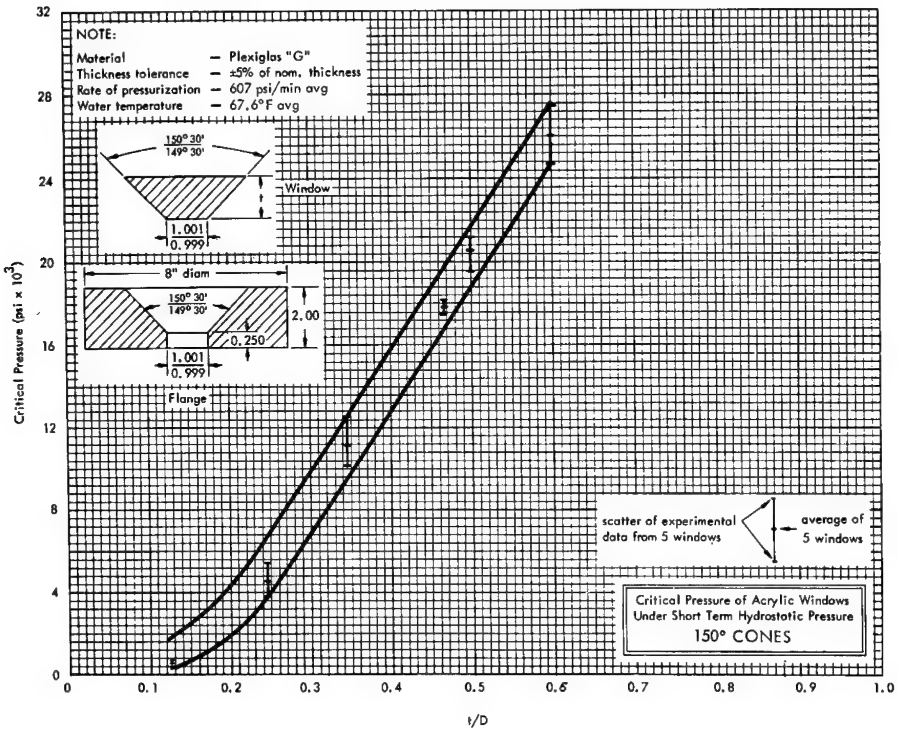


Figure 18. Critical pressures of 1-inch-diameter, 150° conical acrylic windows under short-term hydrostatic pressure.

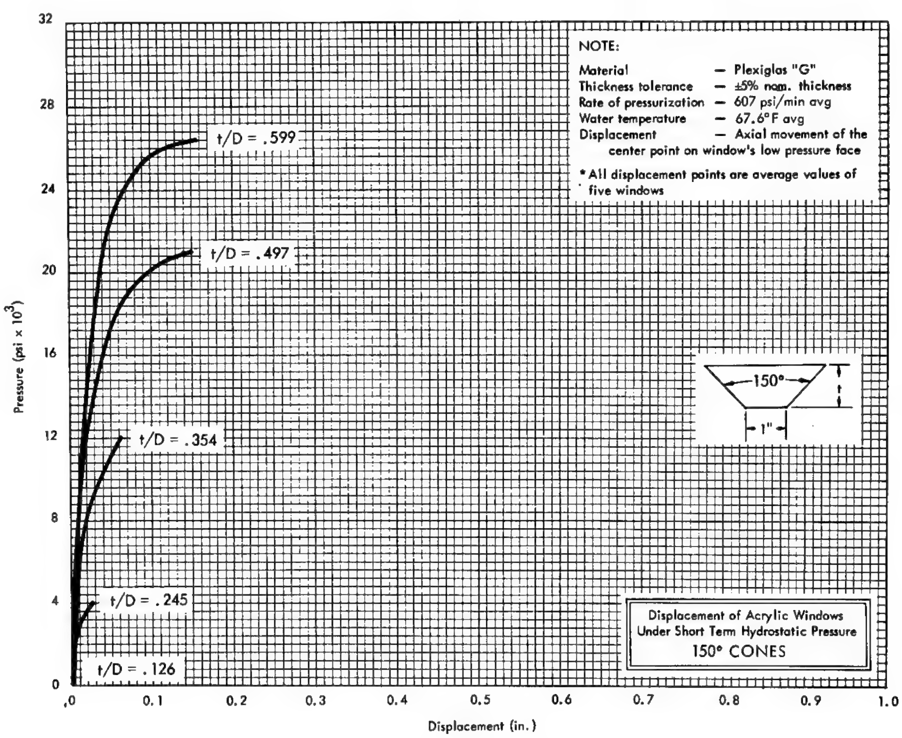


Figure 19. Displacements of 1-inch-diameter, 150° conical acrylic windows under short-term hydrostatic pressure.

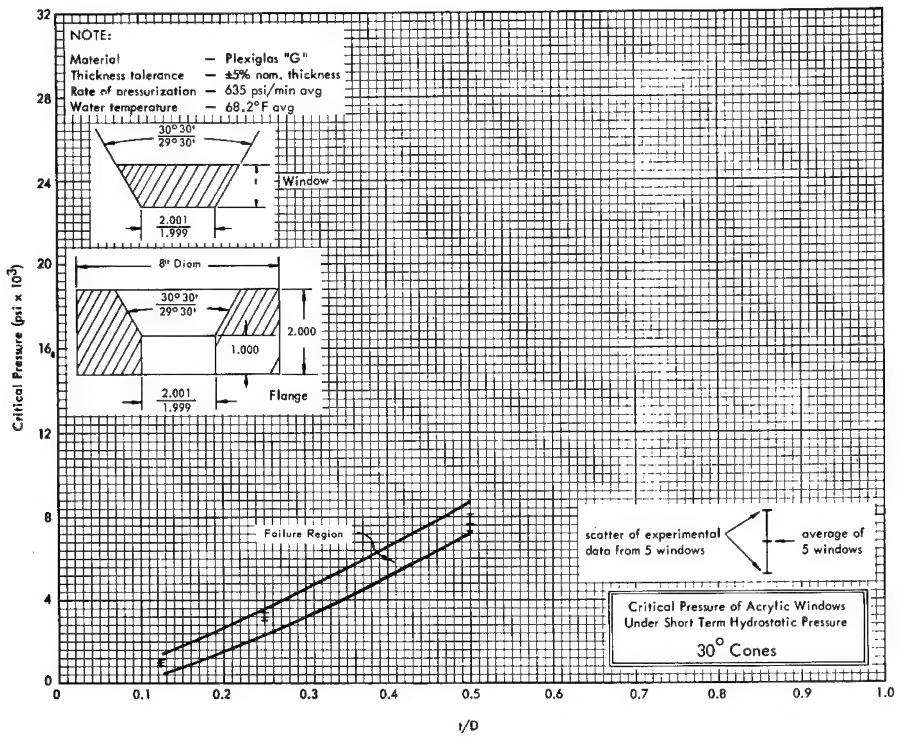


Figure 20. Critical pressures of 2-inch-diameter, 30° conical acrylic windows under short-term hydrostatic pressure.

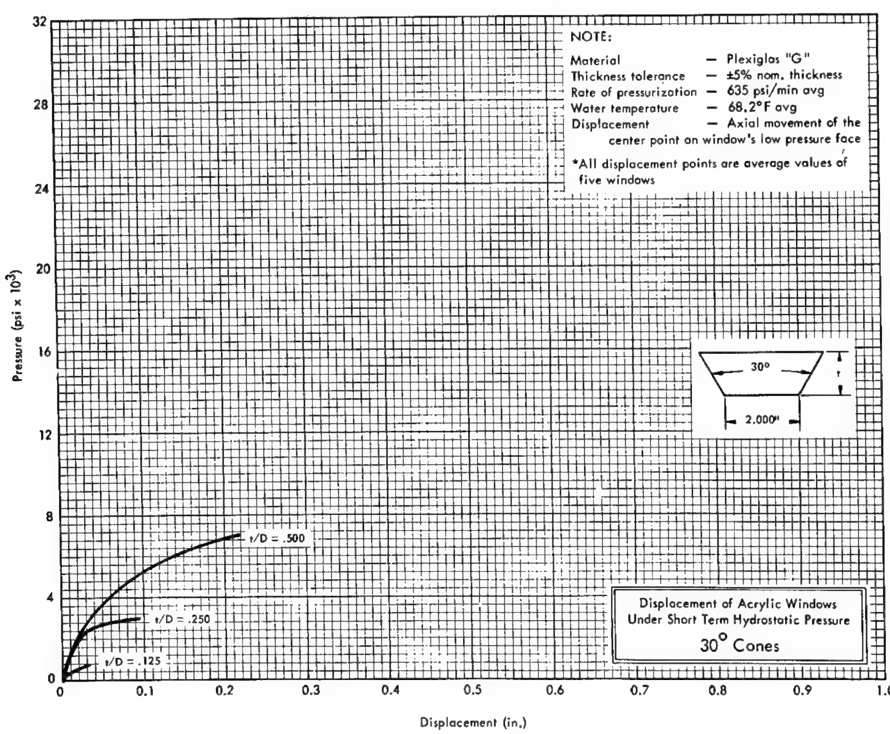


Figure 21. Displacements of 2-inch-diameter, 30° conical acrylic windows under short-term hydrostatic pressure.

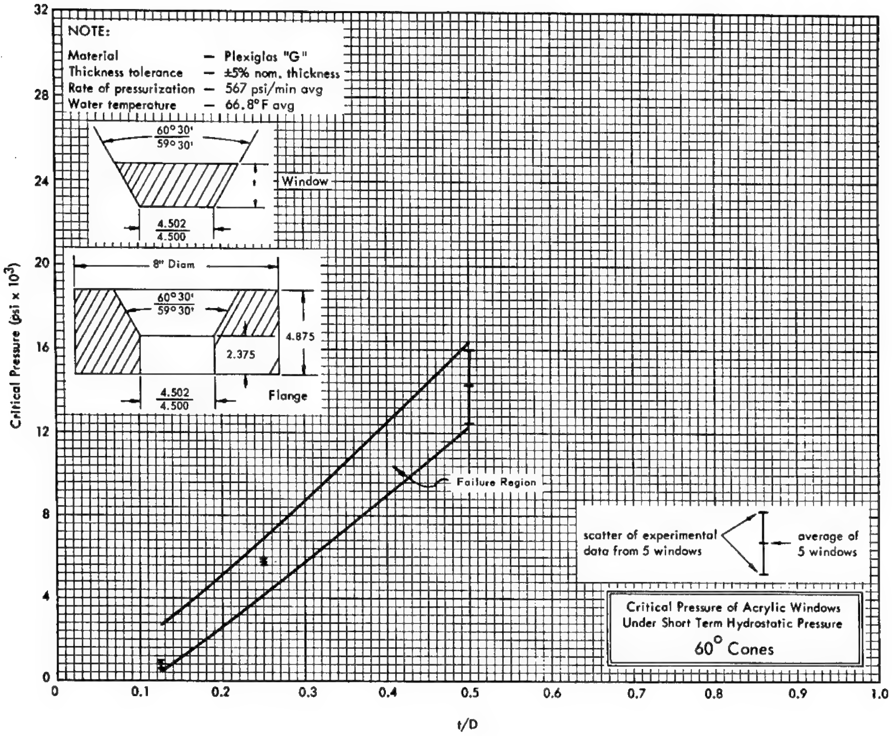


Figure 22. Critical pressures of 4.5-inch-diameter, 60° conical acrylic windows under short-term hydrostatic pressure.

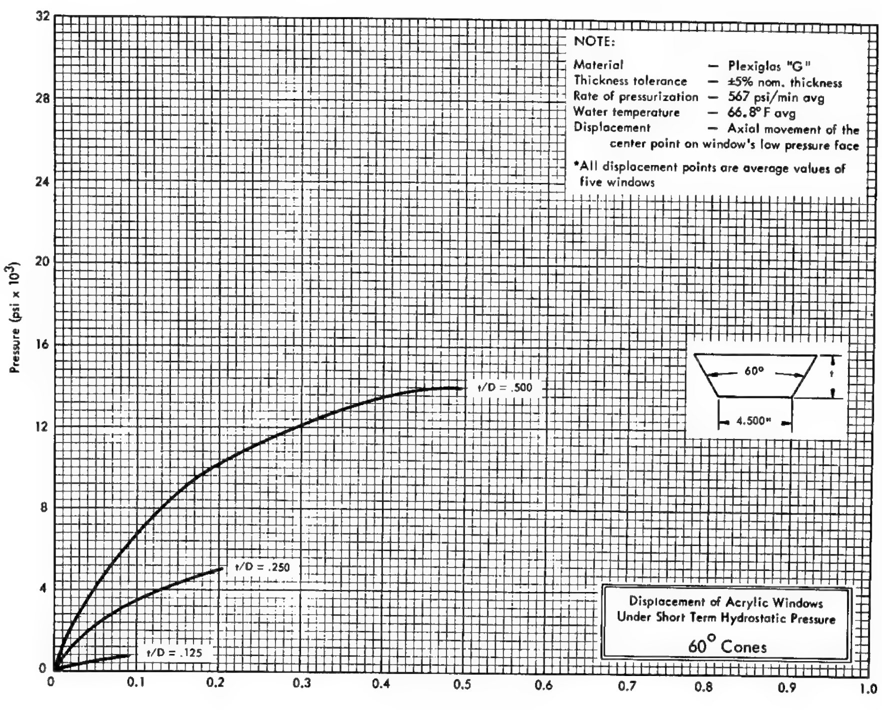


Figure 23. Displacements of 4.5-inch-diameter, 60° conical acrylic windows under short-term hydrostatic pressure.

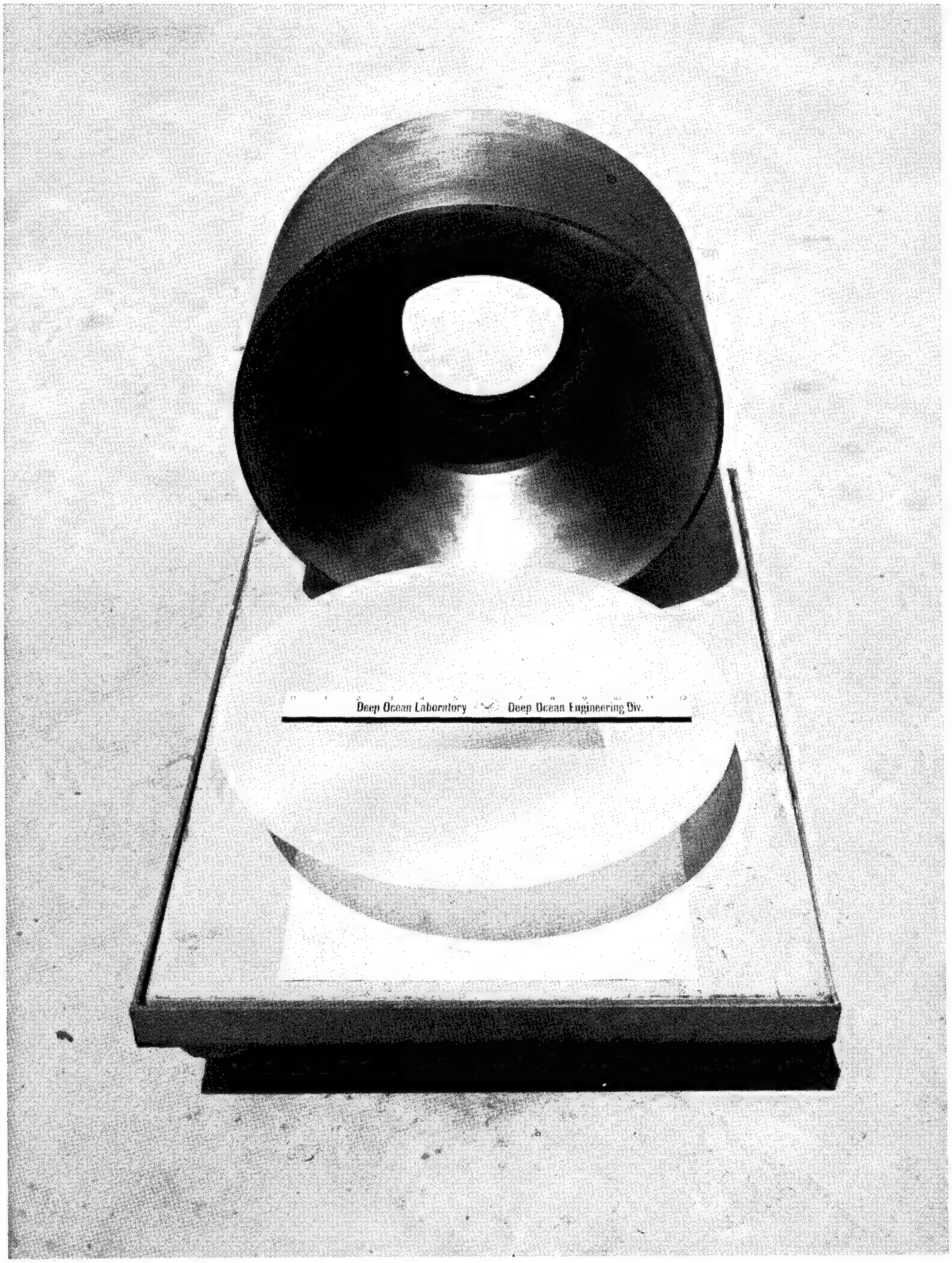


Figure 24. Eight-inch-diameter, 90° conical acrylic window and mounting flange.

Figure 25. End closure assembly for 18-inch-inside-diameter pressure vessel, with 8-inch-diameter, 90° conical acrylic window being secured in mounting flange.

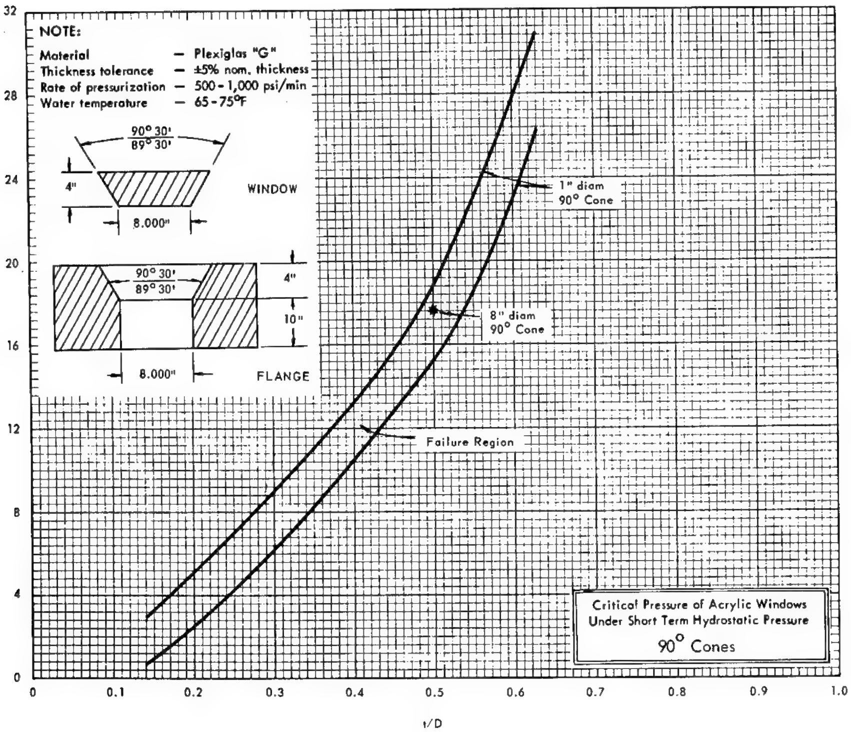


Figure 26. Critical pressure of 8-inch-diameter, 90° conical acrylic window under short-term hydrostatic pressure.

FINDINGS

1. The analysis of experimental data derived from the testing of 1-inch-diameter windows has shown that the displacements of conical acrylic windows larger than 1 inch in diameter, while not directly scalable, can be estimated by application of the proper scaling relationship.

2. The critical pressures of conical acrylic windows in DOL Type I configuration flanges have been found to vary with t/D ratio, as well as the conical angle of the windows. An increase in the t/D ratio is invariably followed by an increase in the window critical pressure, but an increase in the conical angle is not always followed by a critical pressure increase (Figures 27 through 31).

3. The critical pressure of conical acrylic windows under short-term hydrostatic loading increases with a decrease in the temperature of the pressurizing medium. Although sufficient data does not exist to determine accurately how much higher the critical pressure is in the approximately 35° to 40°F than in the approximately 60° to 70°F temperature range, it can be estimated that in all probability it is 10% to 20% higher.

4. The critical pressures of conical acrylic windows with a diameter larger than 1 inch have been found to be the same as those of 1-inch-diameter windows with identical conical angle and t/D ratio.

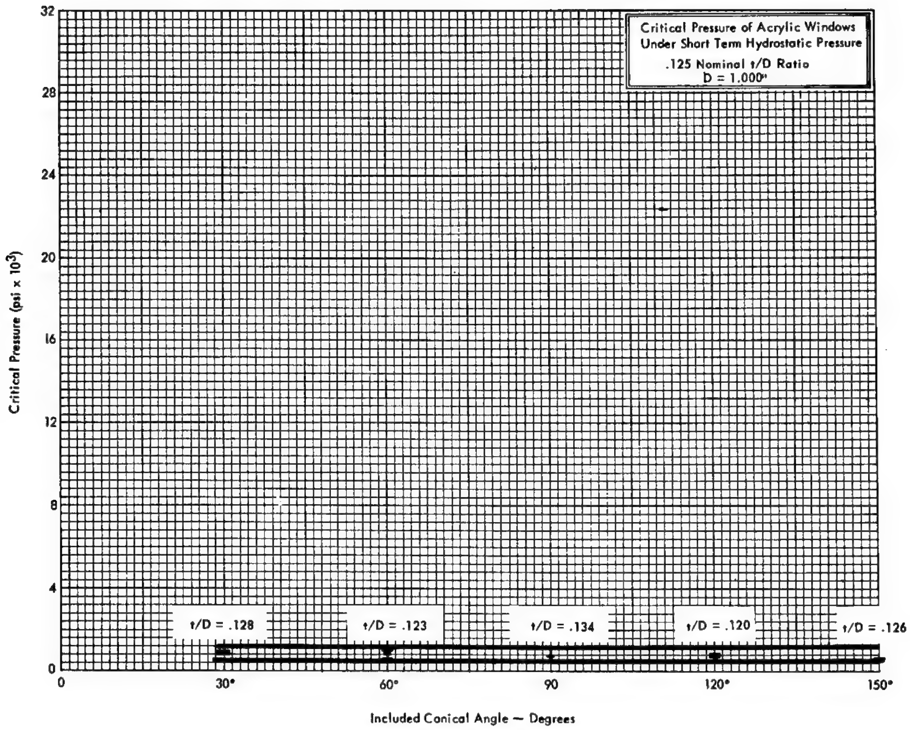


Figure 27. Critical pressures of conical acrylic windows under short-term hydrostatic pressure, 0.125 nominal t/D ratio.

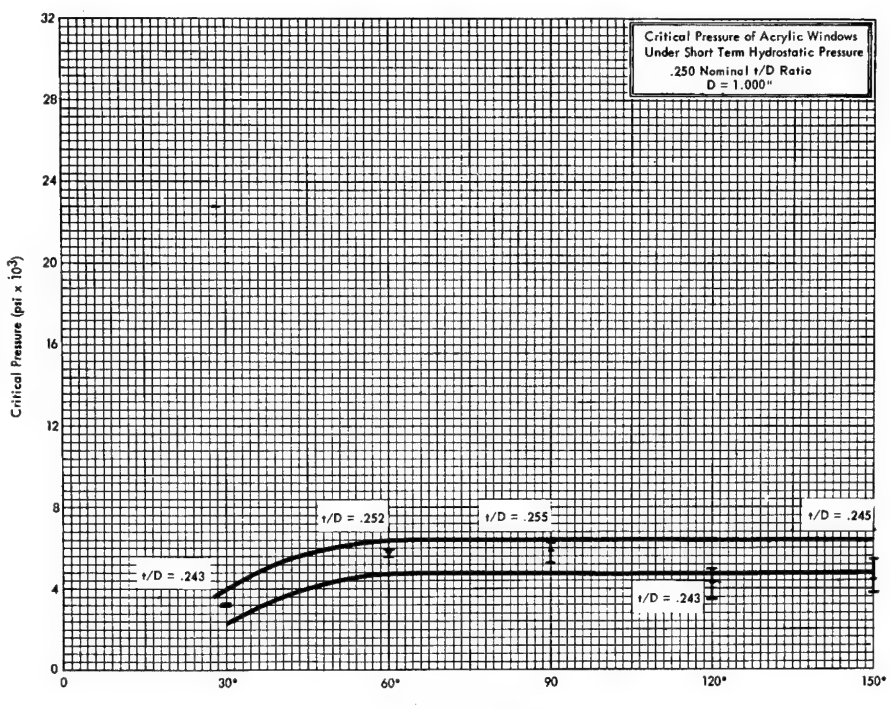


Figure 28. Critical pressures of conical acrylic windows under short-term hydrostatic pressure, 0.25 nominal t/D ratio.

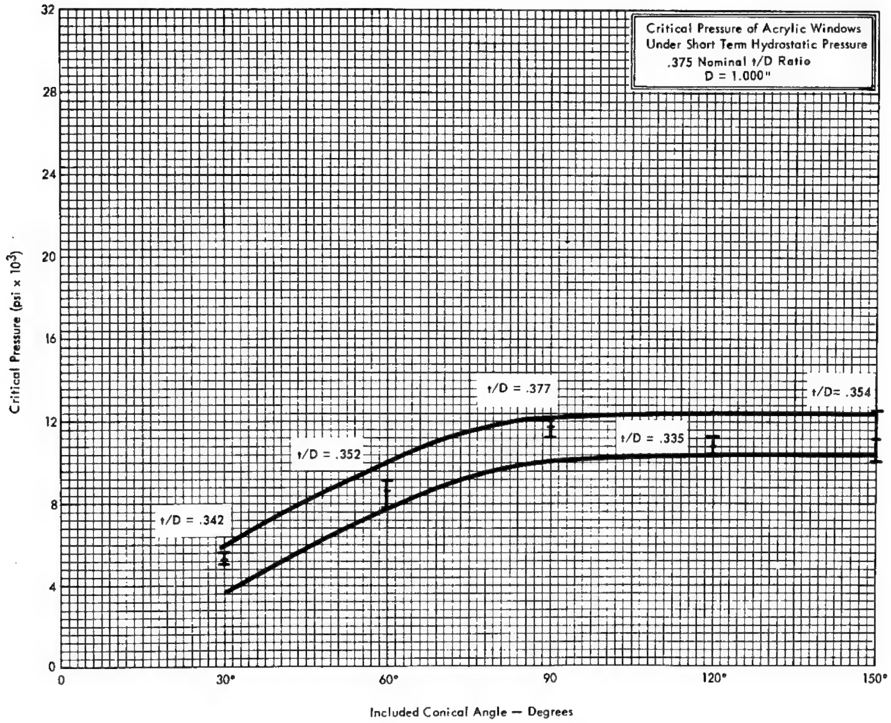


Figure 29. Critical pressures of conical acrylic windows under short-term hydrostatic pressure, 0.375 nominal t/D ratio.

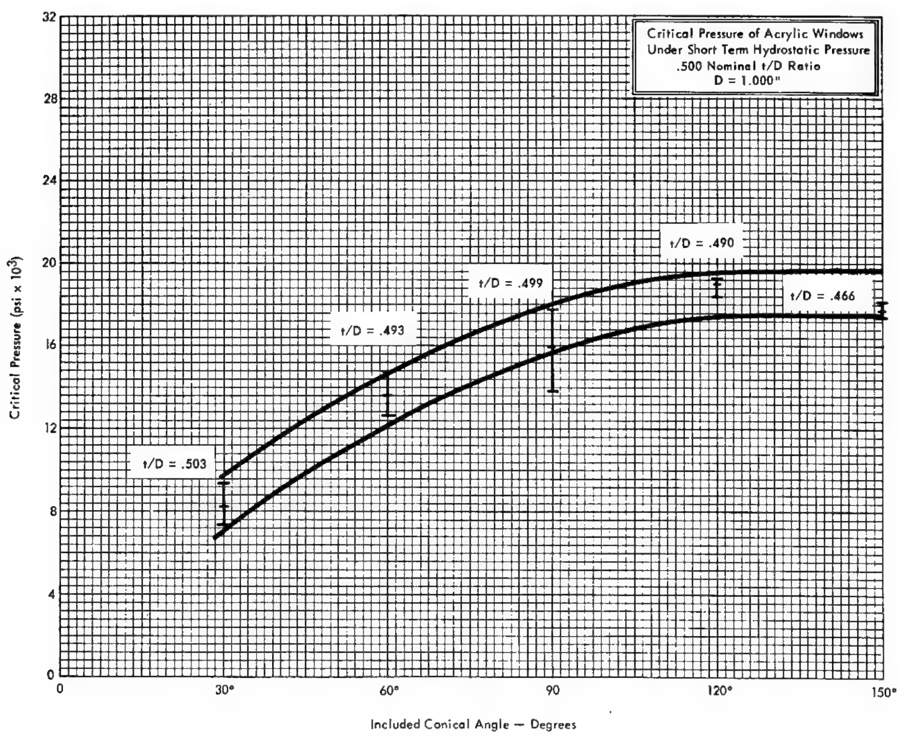


Figure 30. Critical pressures of conical acrylic windows under short-term hydrostatic pressure, 0.5 nominal t/D ratio.

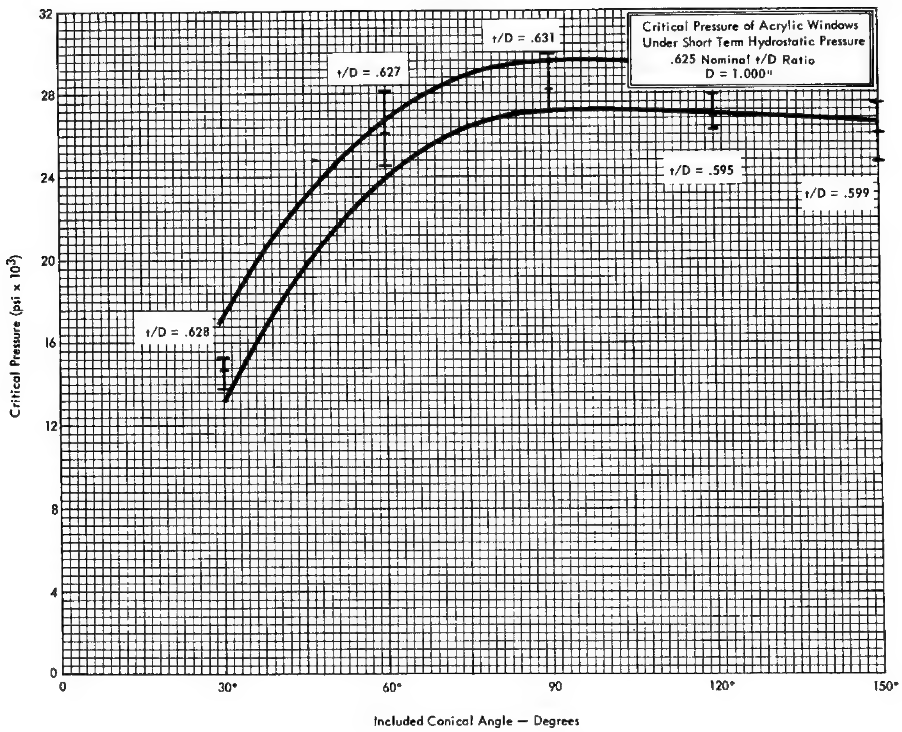


Figure 31. Critical pressures of conical acrylic windows under short-term hydrostatic pressure, 0.625 nominal t/D ratio.

CONCLUSIONS

1. The critical pressures and displacements of the conical acrylic windows presented in this report are valid only for windows mounted in the DOL Type I steel flange. (In this configuration, the pressure-displaced portion of the window has radial support, whatever its extent.) If the DOL Type II steel flange is used to retain the window, much lower critical pressure will result. (The DOL Type II configuration does not provide radial support for the displaced portion.)

2. The critical pressure of large-diameter conical acrylic windows can be predicted directly, with reasonable accuracy, from curves derived from experimental data obtained in the testing of 1-inch-diameter windows provided the larger windows (1) are composed of the same material, (2) have the same t/D ratio and conical angle as the 1-inch-diameter window and, (3) are mounted in a DOL Type I flange.

3. Observation of the material cold flow in the windows tested leads to the conclusion that the optical properties of windows are impaired at pressures considerably below their individual critical pressure. Since optical distortion measurements were not performed with the windows in this study, it is not possible to state quantitatively when the optical distortion of a window progresses to the point where the window loses its value for accurate observation of the hydrospace or the interior of a pressure vessel. Qualitative observations of windows whose testing has been interrupted prior to failure indicate, however, a reasonable assumption to be that the optical properties of windows are not seriously impaired at pressures less than 50% of their critical pressure.

FUTURE STUDIES

Various other studies in the continuing program for investigation of factors which influence the performance of acrylic underwater windows are either in progress or being planned. Studies in progress include the following:

1. Conical acrylic windows under long-term loading (500 to 1, 000 hours) at 20, 000 psi
2. Short-term critical pressure of flat acrylic windows
3. Short-term critical pressure of spherical acrylic windows

Studies in the planning stage cover:

1. Conical acrylic windows under long-term loading (500 to 1, 000 hours) at 10, 000 psi
2. Conical acrylic windows under cyclical pressure loading from 0 to 10, 000 psi
3. Flat acrylic windows under long-term pressure loading at 20, 000 psi
4. Flat acrylic windows under cyclical pressure loading from 0 to 10, 000 psi

Appendix A

PHYSICAL PROPERTIES OF GRADE G PLEXIGLAS*

Maximum tensile strength	10, 500 psi
Maximum flexure strength	16, 000 psi
Maximum compressive strength	18, 000 psi
Maximum shear strength	9, 000 psi
Modulus of elasticity in tension (at strain less than 1%)	450, 000 psi
Modulus of elasticity in compression (at strain less than 1%)	450, 000 psi
Maximum elongation at rupture in tension	4. 9%
Impact strength (Izod milled notch)	0. 4 ft-lb/in. (per inch of notch)
Rockwell hardness	M-93

*Staff Report, Plexiglas Design and Fabrication Data, Bulletin 229g, Rohm and Haas Co., August 1961.

Appendix B

MODES OF FAILURE OF CONICAL ACRYLIC WINDOWS

In the following descriptions of failure modes for conical acrylic windows, certain terms have special definitions. Cold flow is the plastic deformation of the acrylic window material at room temperature resulting from application of high hydrostatic pressure to the window high-pressure face while the low-pressure face remains at atmospheric pressure. Cratering denotes the formation of a roughly circular depression in the center of the window high-pressure face as a result of cold flow. A fracture cone is a cone-shaped fracture surface inside the body of a window observed at the termination of the test.

In the photographs supplementing the descriptions of the failure modes, the grid pattern seen on many of the high-pressure window faces is the reflection of a grid cast there at the time the photographs were made. This reflection is a device intended to reveal any cratering or other irregularity on the high-pressure face, as a result of cold flow or partial mechanical failure. Any irregularity in the mirrorlike window surface is made apparent by a distorted reflection of the regular square pattern of the grid.

One-Inch-Diameter, 30° Conical Windows

All the 1-inch-diameter, 30° conical windows failed explosively, with all fragments ejected from the pressure vessel. An interesting feature was the lack of deformation on the high-pressure faces of these windows. Examination of a test specimen removed from the flange after being pressurized to approximately 85% of its critical pressure revealed almost no cold-flow cratering on the high-pressure face (Figure B-1) but a considerable amount on the low-pressure face, as evidenced by the moderately long, cylindrical extrusion (Figure B-2). The low-pressure face also exhibited the circumferential cracks typical of low-pressure faces of all conical acrylic windows regardless of their included angle size. Since the deformation was noted at a pressure very close to the critical pressure of the window, it is reasonable to assume that the failure of the 30° window does not result from any deep cratering of the high-pressure face, but propagation of cracks from the bearing surfaces to the interior of the window. When these cracks, already apparent in the specimen examined, penetrate to the window center, fracturing of the window occurs followed by ejection of the fragments from the mounting flange.

One-Inch-Diameter, 60° Conical Windows

The mode of failure of the 1-inch-diameter, 60° conical windows was not as uniform as that of the 30° windows, but varied with the t/D ratio. Windows with low t/D ratios, 0.125 and 0.25, failed by fracturing in such a manner that only the center portion was ejected, with the rest of the window staying in the mounting flange in the form of a continuous ring. The low-pressure face of these windows (Figure B-3) exhibited a conical fracture surface, while the high-pressure face remained flat without trace of cold flow, showing only a round hole with ragged edges in the center (Figure B-4).

The 60° windows with an intermediate t/D ratio (0.375 to 0.625) also fractured in the center, so that only the center portion of the window was ejected, while the other fragments remained in the flange in most cases. The windows with the intermediate t/D ratios had very severe cold-flow symptoms on the high-pressure face (Figures B-5 and B-6). This extensive cold flow was a bona fide indication that the proportions of the window were such that the failure of the material had to occur in the plastic range of its properties. The low-pressure face of the windows with intermediate t/D ratios had the same type of conical fracture cavity as the low t/D ratio, 60° windows (Figure B-7). The cold flow on the high-pressure face, when considered together with the conical fracture cavity on the low-pressure face, indicated that, although the amount of cold flow increased with the increase of t/D ratio, the actual mechanism of fracture was the same.

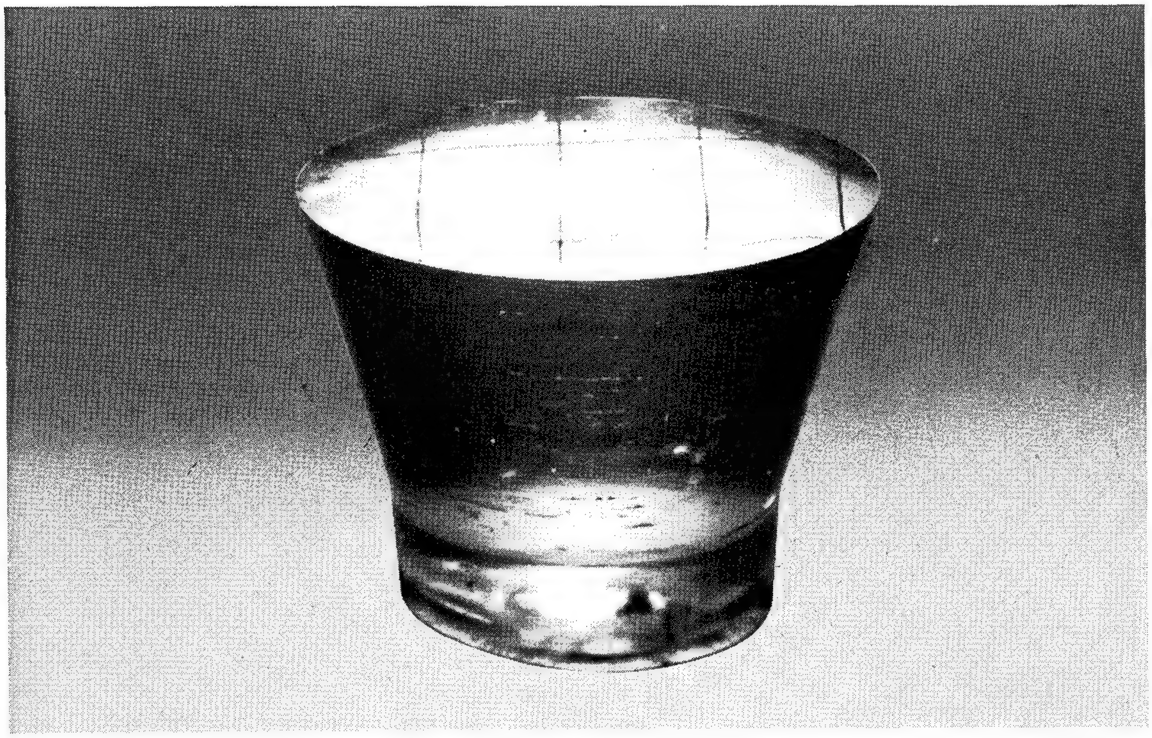


Figure B-1. Arrested failure of 1-inch-diameter, 30°, 1.0 t/D ratio window at 24, 000 psi, high-pressure face.

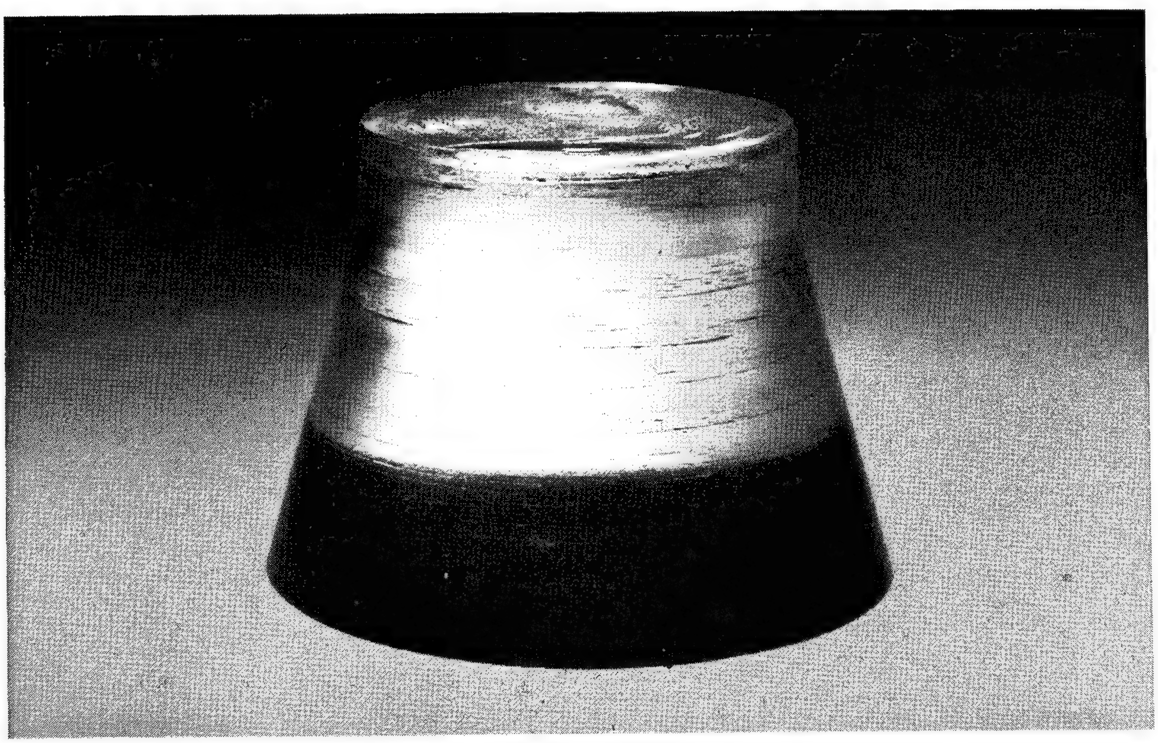


Figure B-2. Arrested failure of 1-inch-diameter, 30°, 1.0 t/D ratio window at 24, 000 psi, low-pressure face.

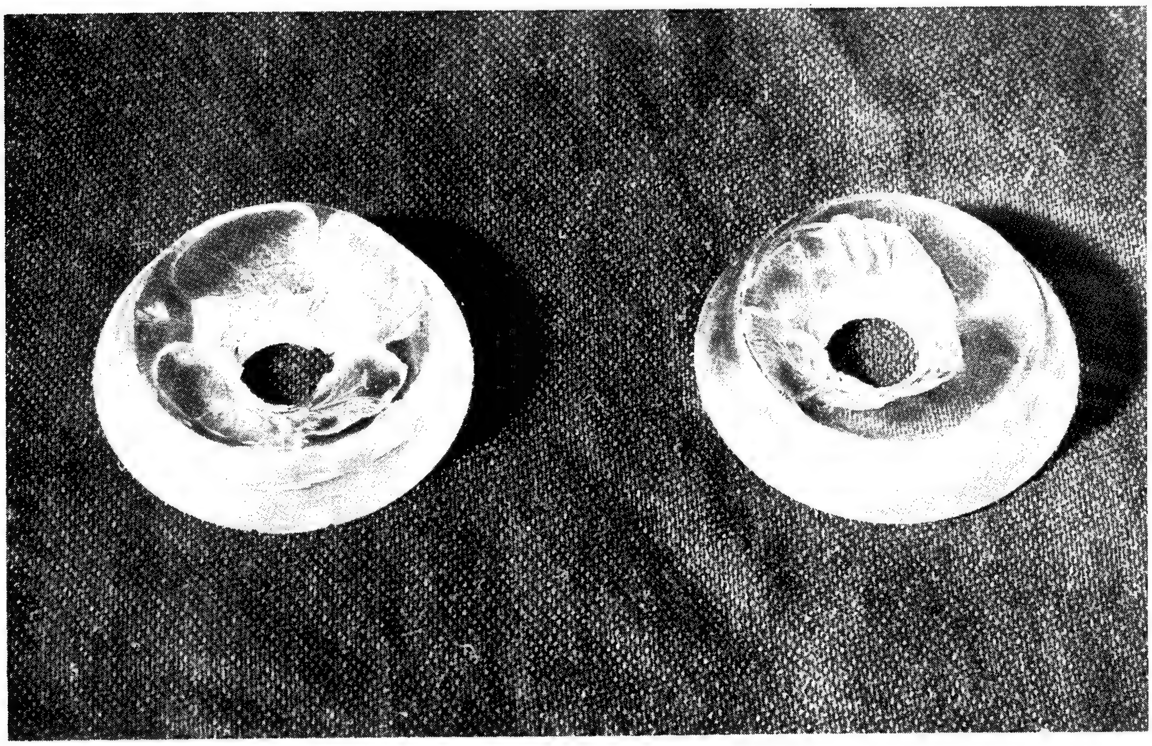


Figure B-3. Failed 1-inch-diameter, 60°, 0.25 t/D ratio windows, low-pressure faces.

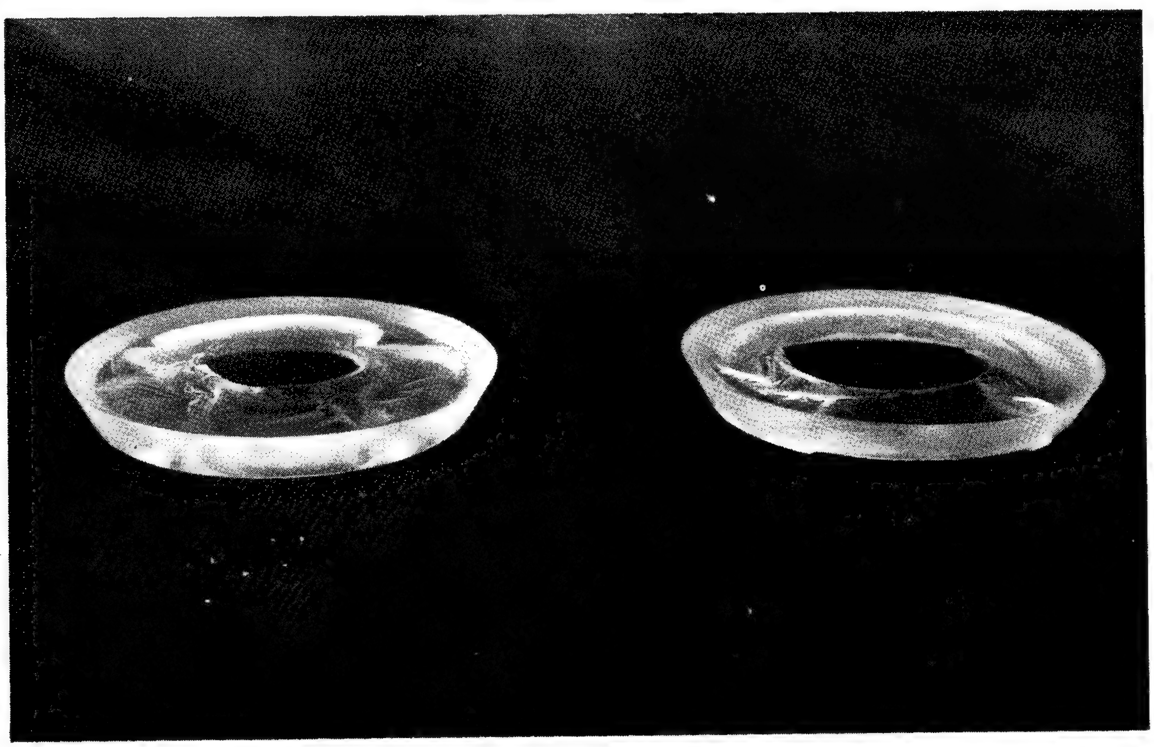


Figure B-4. Failed 1-inch-diameter, 60°, 0.25 t/D ratio windows, high-pressure faces.

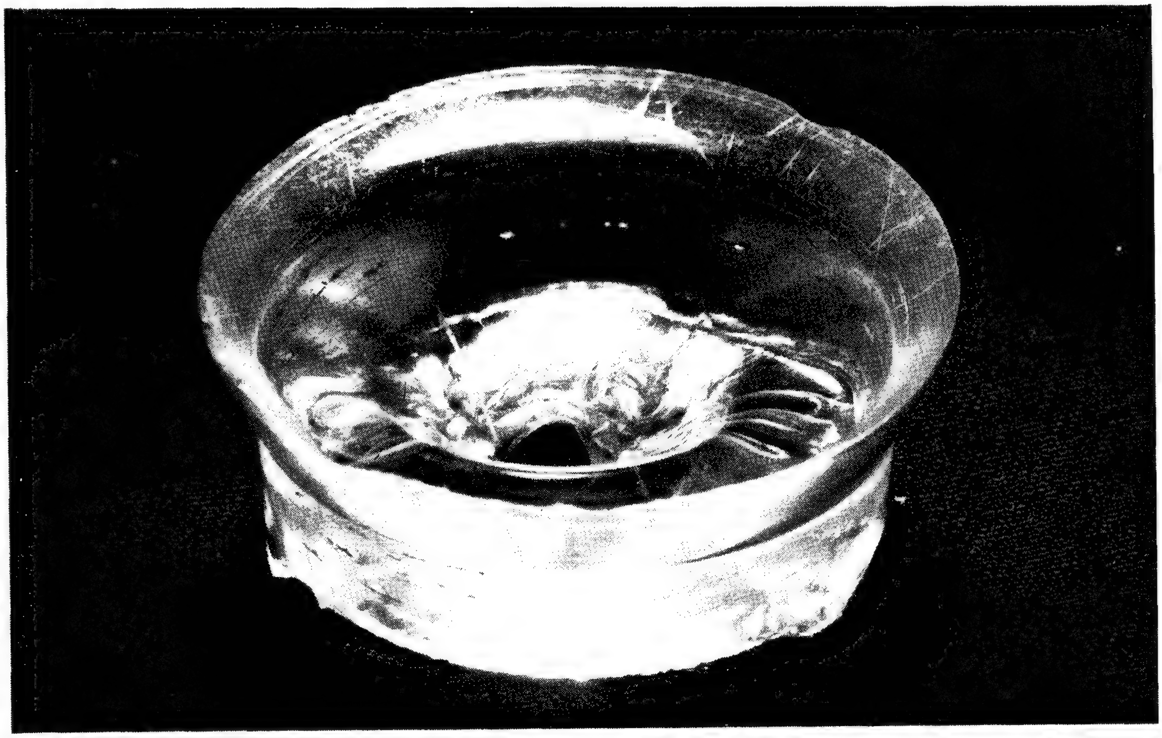


Figure B-5. Failed 1-inch-diameter, 60°, 0.35 t/D ratio window, high-pressure face.

Figure B-6. Arrested failure of 1-inch-diameter, 60°, 0.625 t/D ratio window at 26, 600 psi, high-pressure face.

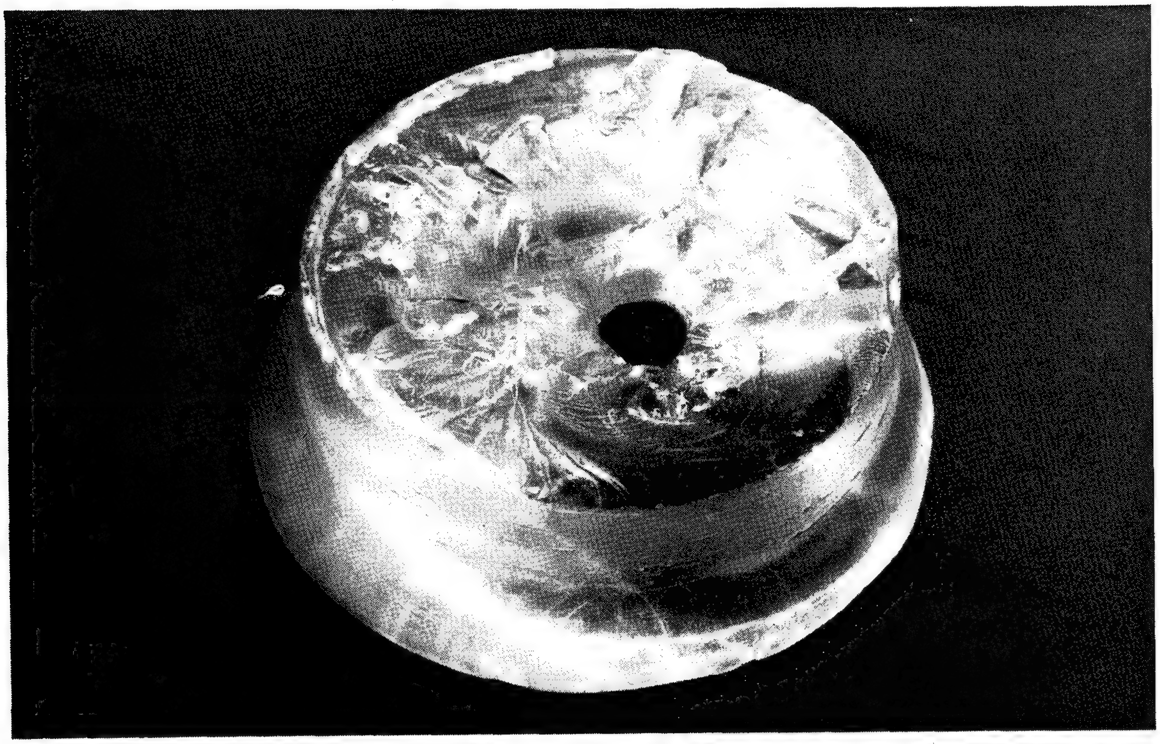


Figure B-7. Failed 1-inch-diameter, 60°, 0.35 t/D ratio window, low-pressure face.

When the 60° windows with high t/D ratios were observed during tests, it was found they behaved in a manner similar to the low and intermediate t/D ratio windows except that no pieces of window remained in the flange after testing. The cold flow, of course, would be more pronounced than in either the low or intermediate ratio windows, as the proportions of the window were such that a cold flow had to occur before a conical fracture on the low-pressure face could be initiated. Even windows pressurized to 30% to 50% below the critical pressure showed considerable extrusion into the cylindrical cavity of the mounting flange (Figure B-8). When the large amount of cold flow on the low-pressure face of the high t/D ratio (1.0) window (Figure B-8) was compared with the small amount of cold flow on the high-pressure face (Figure B-9), the tentative conclusion was reached that the high t/D ratio, 60° window underwent three phases of deformation. The first phase was characterized by the uniform radial compression of the window caused by hydrostatic pressure forcing the acrylic plastic into the cylindrical cavity, resulting in the large amount of extrusion there. Very little, or no cold flow occurred on the high-pressure face of the window during that phase, as the face still remained essentially flat without noticeable crater. The duration of the first phase was probably to 50% of the critical pressure of the window.

The second phase, lasting from approximately 50% of critical pressure to just below the critical pressure, was characterized by extensive cold flow on the low-pressure face (Figure B-10), while the crater on the high-pressure face became noticeable (Figure B-11). Considerable cracking of the window body occurred in the transition zone between the conical and cylindrical sections of the window, as well as on the low-pressure face. The cracks in the transition zone (Figure B-10) extended at an angle from the bearing surface of the window into its interior, forming the incipient conical fracture surface. The cracks on the low-pressure face, on the other hand, extended along the circumference of the face, forming several continuous-crack circles.

Figure B-8. Arrested failure of 1-inch-diameter, 60°, 1.0 t/D ratio window at 22, 000 psi, low-pressure face. (Phase 1 of deformation.)

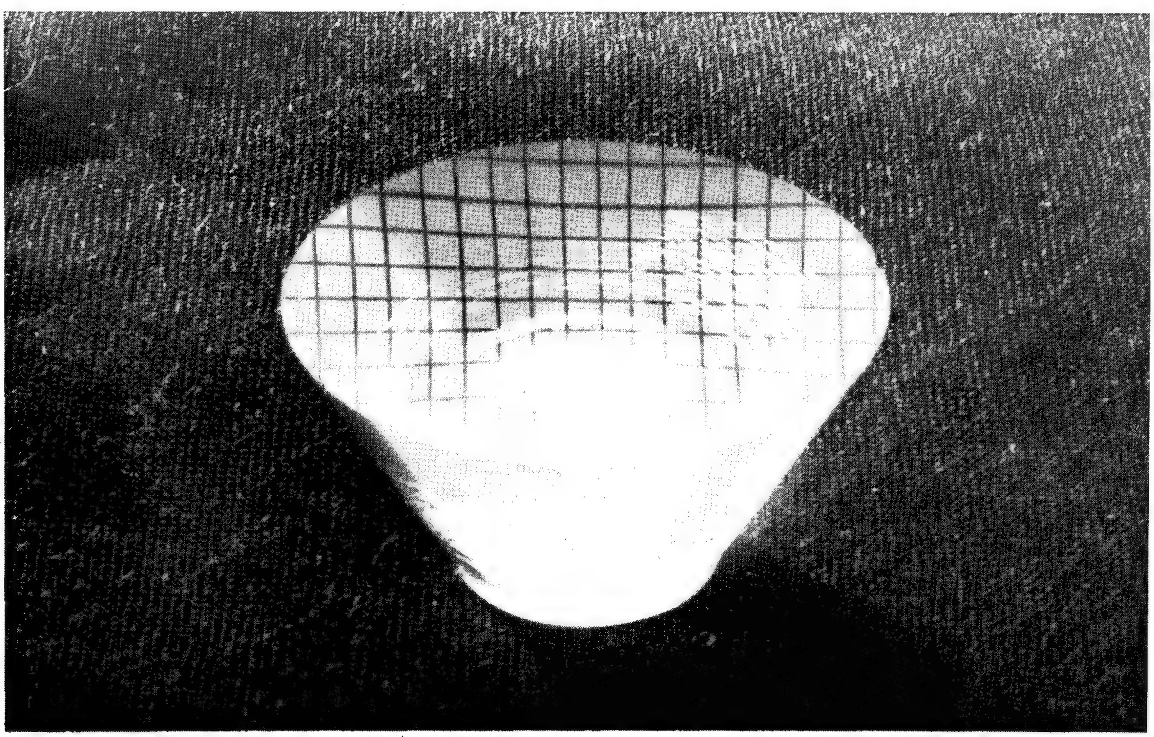


Figure B-9. Arrested failure of 1-inch-diameter, 60°, 1.0 t/D ratio window at 22, 000 psi, high-pressure face. (Phase 1 of deformation.)

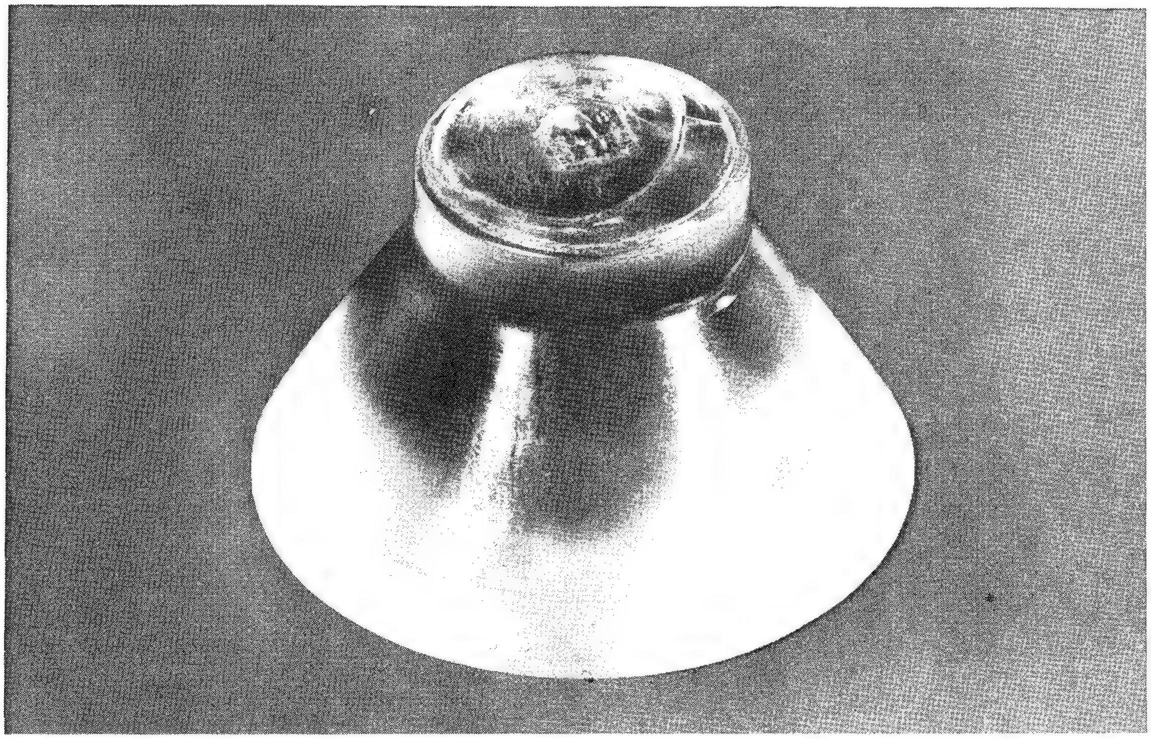


Figure B-10. Arrested failure of 1-inch-diameter, 60°, 1.0 t/D ratio window at 28, 000 psi, low-pressure face. (Phase 2 of deformation.)

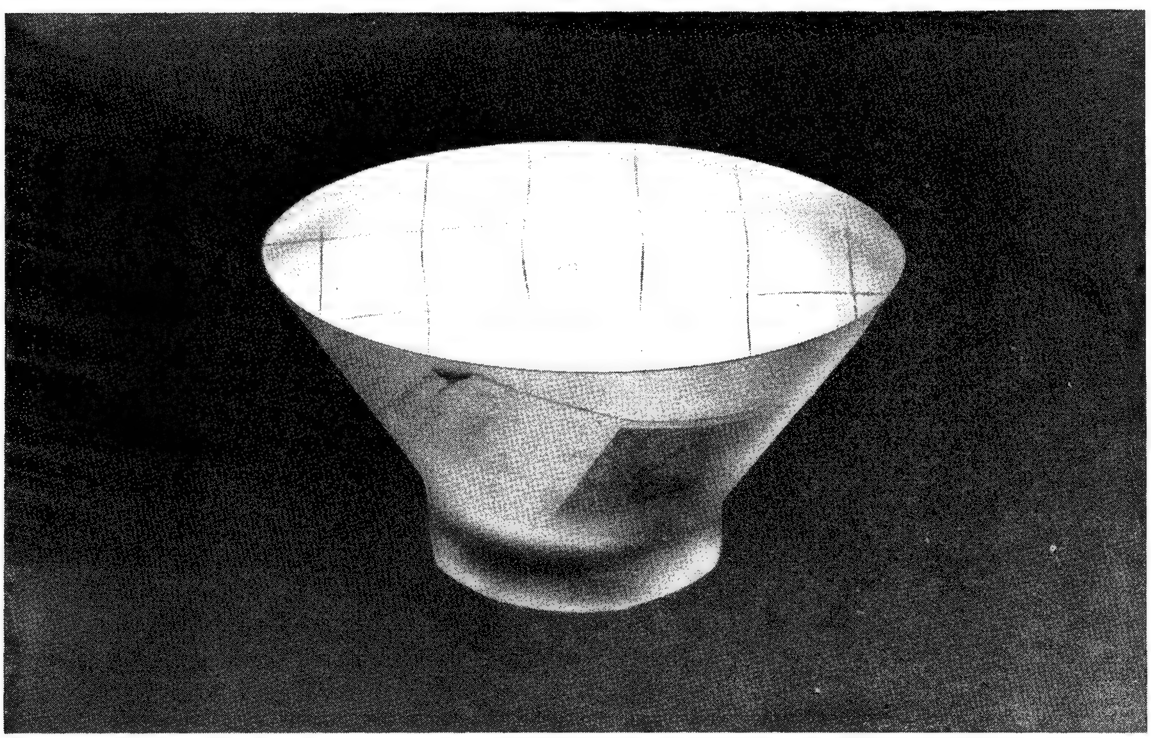


Figure B-11. Arrested failure of 1-inch-diameter, 60°, 1.0 t/D ratio window at 28, 000 psi, high-pressure face. (Phase 2 of deformation.)

The third phase of deformation of the high t/D ratio, 60° windows took place at the point of critical pressure. At that time, the cold-flow crater in the high-pressure face had progressed to such a depth of the window body that the small cracks at the bottom of the crater united with the cracks progressing from the window bearing surface at the cone-to-cylinder transition zone, and a conical fracture surface was created. When the conical fracture surface was generated, the center portion of the window was ejected first, followed immediately by the remainder propelled by the high-velocity stream of water.

One-Inch-Diameter, 90° Conical Windows

The 1-inch-diameter, 90° conical windows failed in a manner similar to the 60° windows. The low t/D ratio windows failed by ejection of the center portion of the window with the rest remaining in the flange. The intermediate and high t/D ratio windows in most cases failed by complete fragmentation. The low t/D ratio windows failed without cold flow (Figures B-12 and B-13), while those with intermediate and high t/D ratios exhibited cold flow. The phases of window deformation were the same as in the 60° windows, except that the magnitudes of deformation were different for the same t/D ratios. Again, as in the 60° windows, one could see the minute cold flow on the high- and low-pressure faces in Phase 1 (Figures B-14 and B-15) and the fair amount of cold flow in Phase 2 (Figures B-16 and B-17). The basic difference in Phases 1 and 2 of the 90° windows from the corresponding phases of the 60° windows lay in the amount of cold flow at the same pressure. While the cold flow was extensive for the 60° windows, for the 90° windows only slight indication of it was evident. Thus, when a comparison was made between a 60° and a 90° window from interrupted failure tests, one could see that although both windows had the same t/D ratio (0. 625) and both had been pressurized to 26, 600 psi prior to removal from the vessel, only the 60° window exhibited cold flow extensively on both the high-pressure and low-pressure faces (Figures B-6 and B-18).

One-Inch-Diameter, 120° Conical Windows

In the $0.125 \leq t/D \leq 0.625$ range of ratios, conical windows failed consistently by fracturing in the middle, so that the center portion was ejected (Figures B-19 through B-24) while the remainder of the window was retained by the mounting flange. This was quite different from the failure of 60° and 90° windows, where the center portion of the window was ejected only in the low and intermediate $0.125 \leq t/D \leq 0.375$ range of ratios, while at the high t/D ratios the whole window was invariably ejected.

During some of the testing (arrested failures) it was possible to retrieve the center portion. Close inspection of this portion revealed that the mechanism of failure of the 120° windows was quite complex, as the center portion exhibited, in addition to the cold-flow crater on the high-pressure face, a conical fracture cavity on the low-pressure face which also showed signs of cold-flow displacement into the cylindrical opening in the mounting flange.

Thus, a typical 120° window, as exemplified by the 0. 5 t/D ratio window in Figures B-25 and B-26, had two fracture cones, an inner one and an outer one. The latter surrounded the whole center portion of the window generally ejected from the flange in small fragments. In the example shown of a typical 120° window failure, the center portion, including the inner fracture cone, was not ejected from the flange, but retrieved from a basket hung immediately below it on the high-pressure side of the window. The reason in this case for the center portion of the window not being ejected was probably the fact that the apex of the inner fracture cone on the low-pressure face met the apex of the cold-flow crater on the high-pressure face, creating a passage for the fluid and thus permitting the pressure in the vessel to be relieved a split second before the center portion of the specimen was extruded sufficiently to be ejected through the cylindrical opening in the flange.

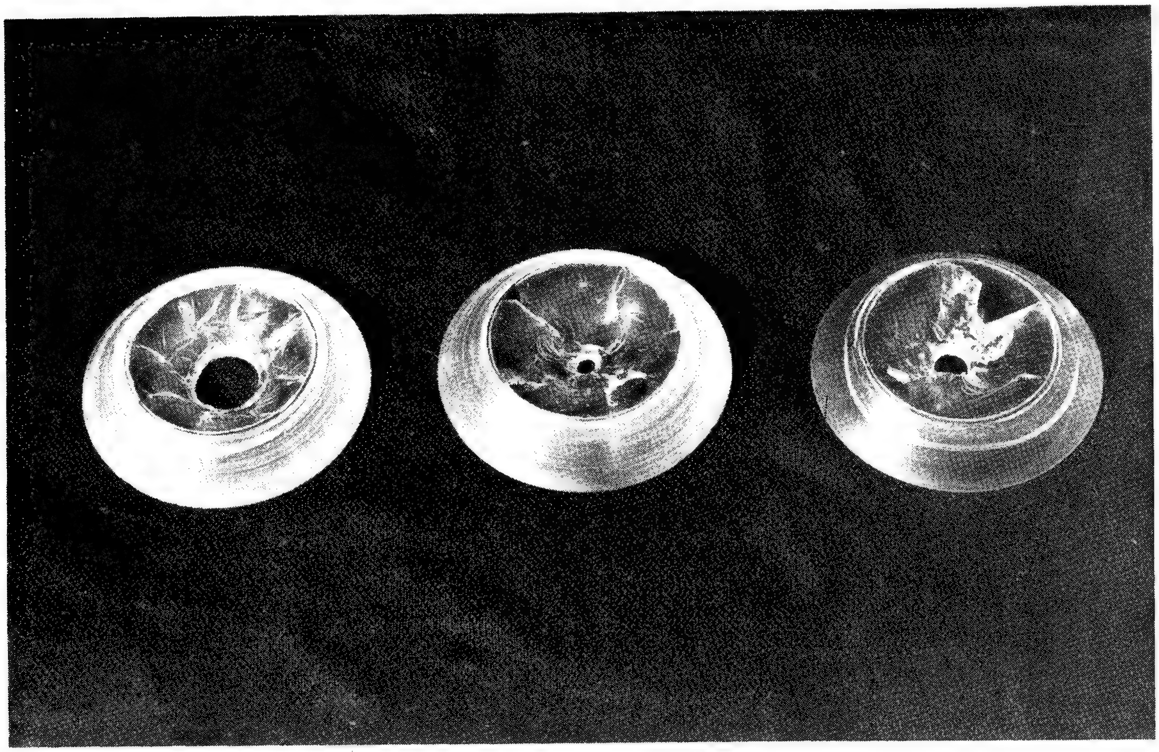


Figure B-12. Failed 1-inch-diameter, 90°, 0.25 t/D ratio windows, low-pressure faces.

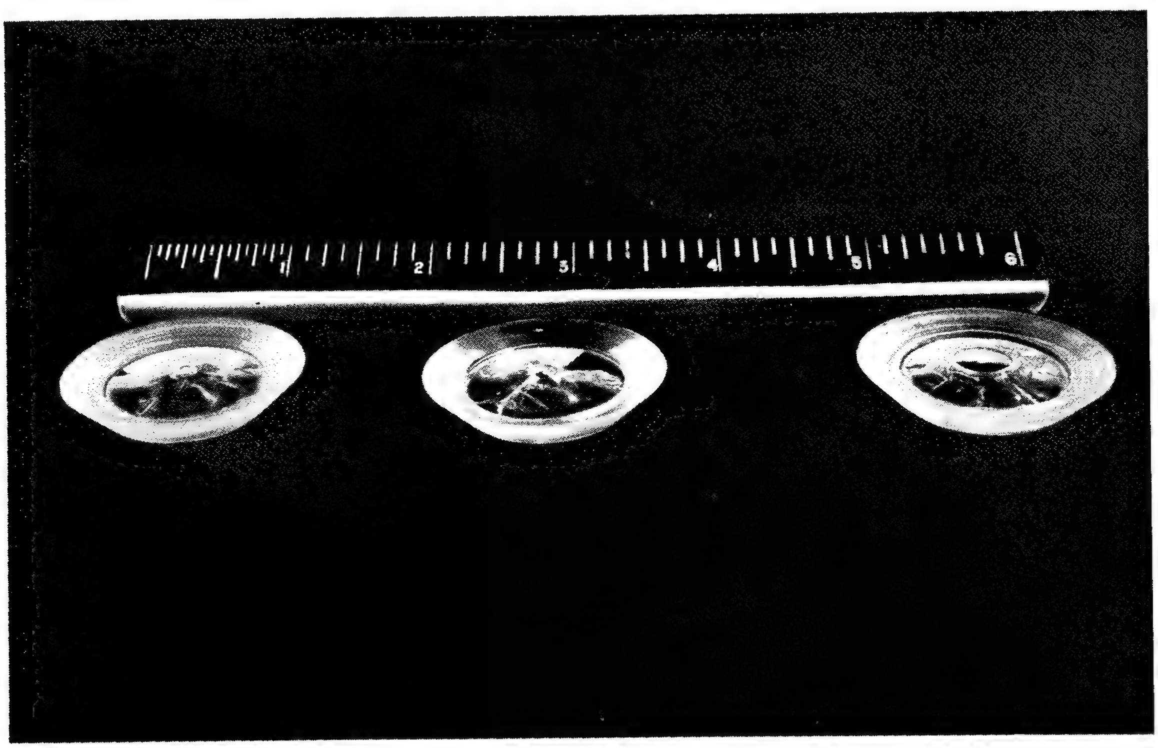


Figure B-13. Failed 1-inch-diameter, 90°, 0.25 t/D ratio windows, high-pressure faces.

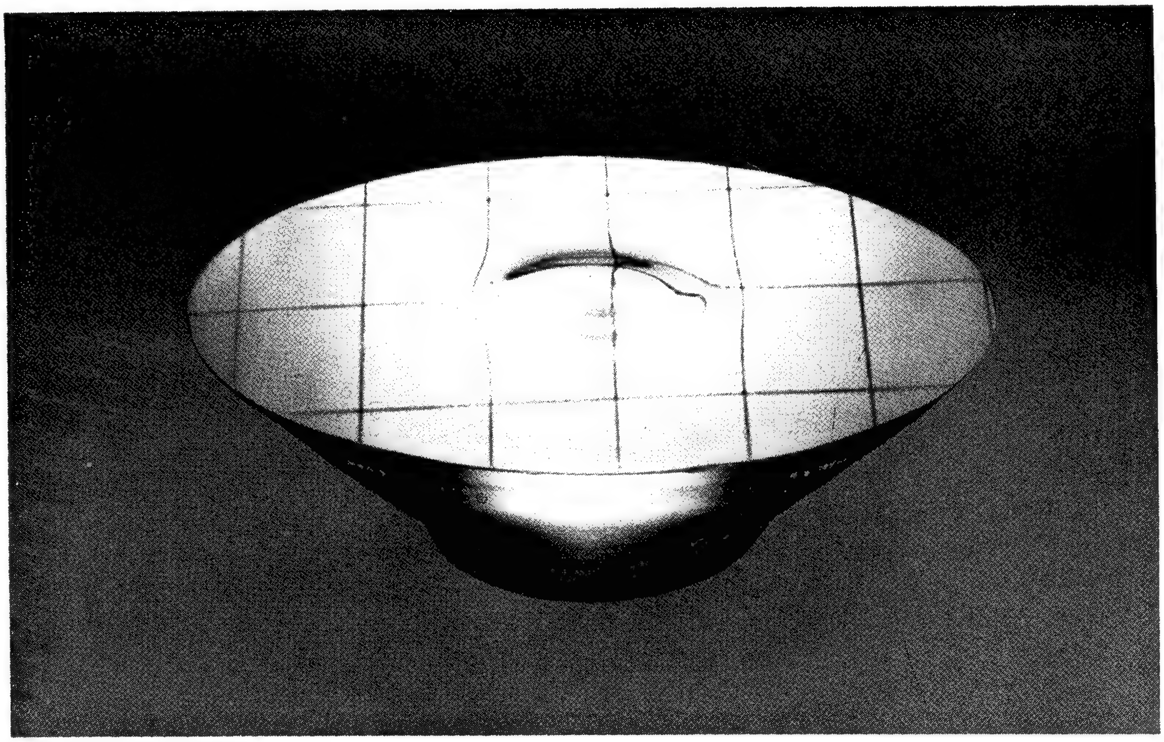


Figure B-14. Arrested failure of 1-inch-diameter, 90°, 0.625 t/D ratio window at 26, 500 psi, high-pressure face. (Phase 1 of deformation.)

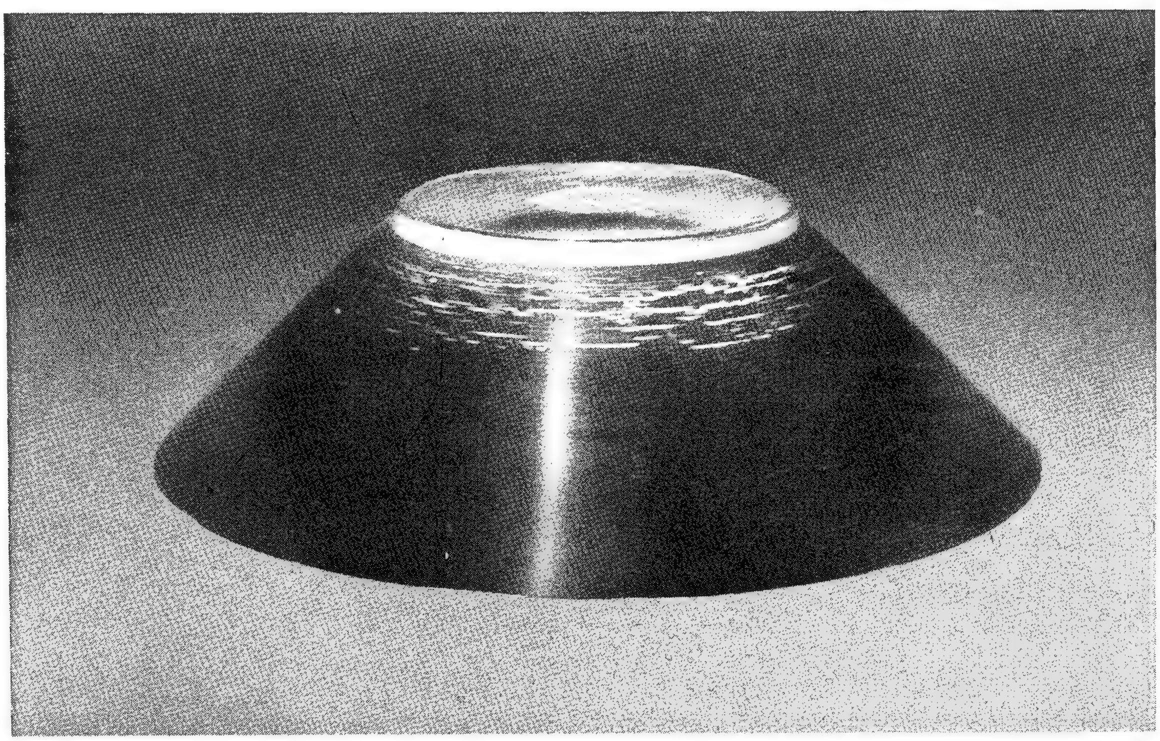


Figure B-15. Arrested failure of 1-inch-diameter, 90°, 0.625 t/D ratio window at 26, 500 psi, low-pressure face. (Phase 1 of deformation.)

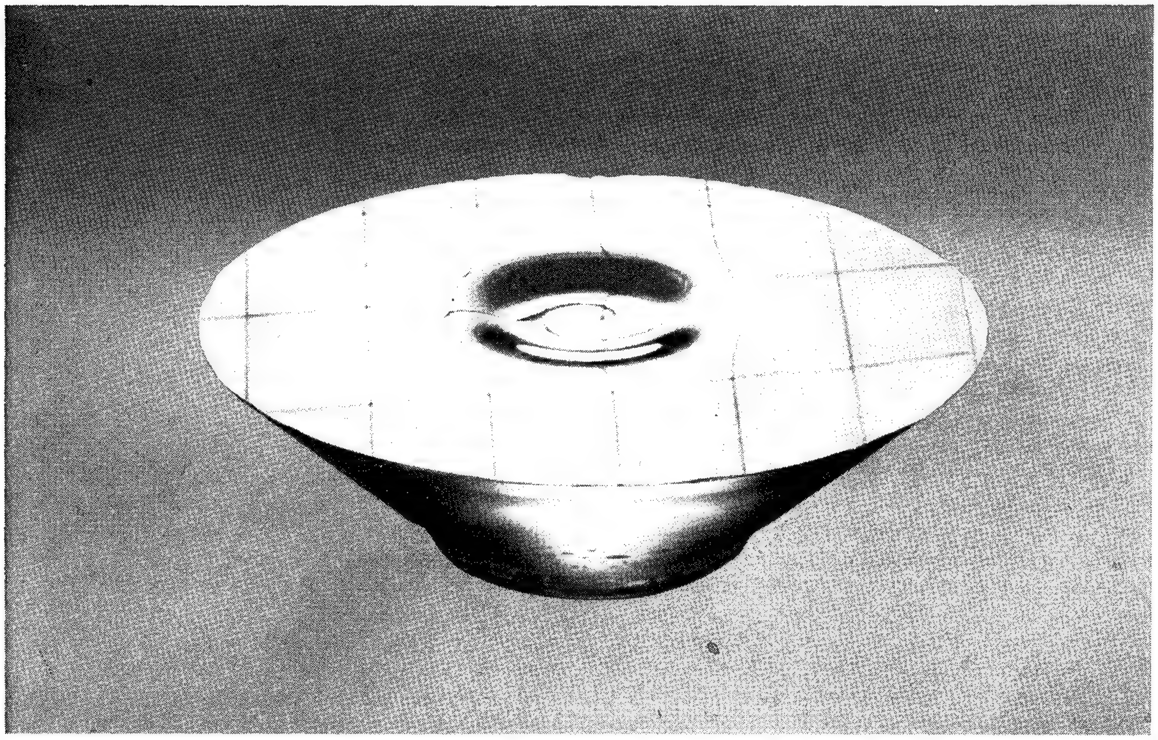


Figure B-16. Arrested failure of 1-inch-diameter, 90°, 0.625 t/D ratio window at 28,600 psi, high-pressure face. (Phase 2 of deformation.)

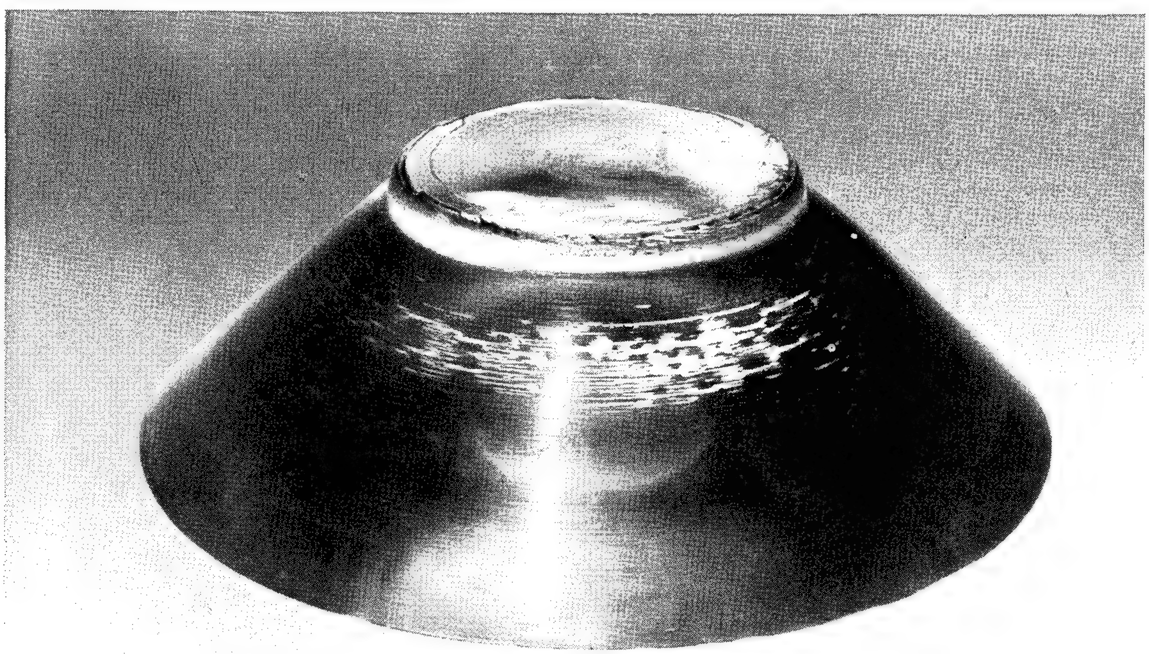


Figure B-17. Arrested failure of 1-inch-diameter, 90°, 0.625 t/D ratio window at 28,600 psi, low-pressure face. (Phase 2 of deformation.)

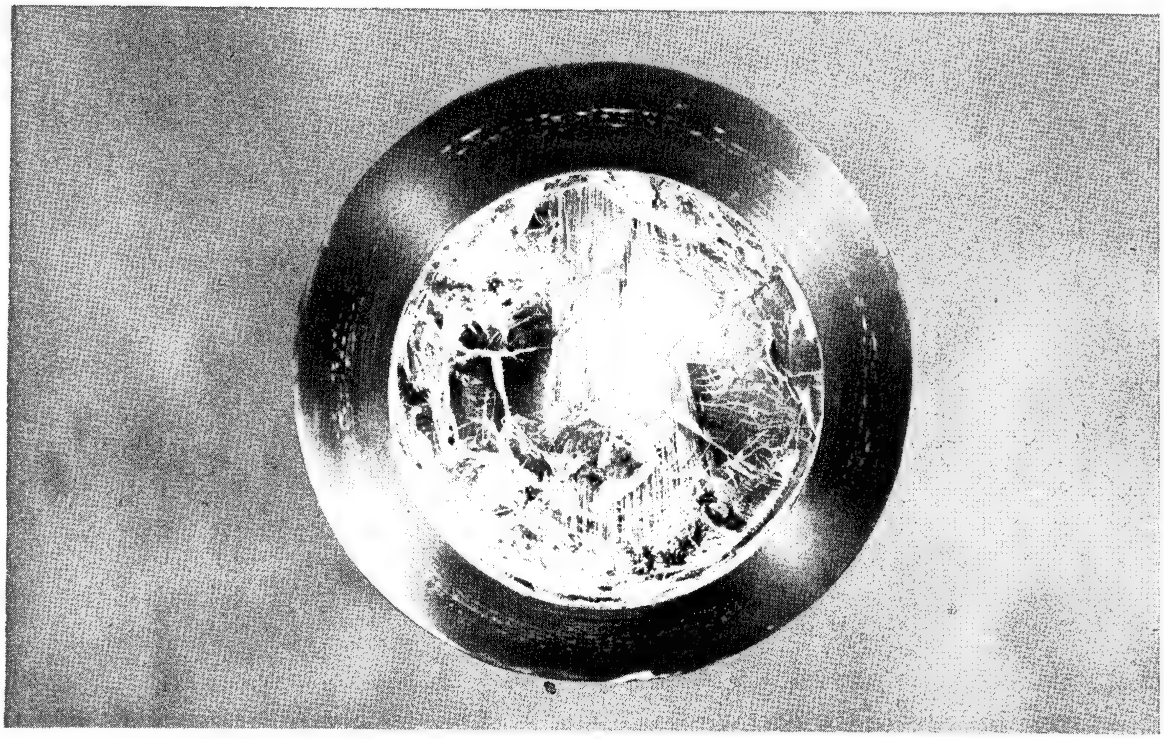


Figure B-18. Arrested failure of 1-inch-diameter, 60°, 0.625 t/D ratio window at 26, 600 psi, low-pressure face.

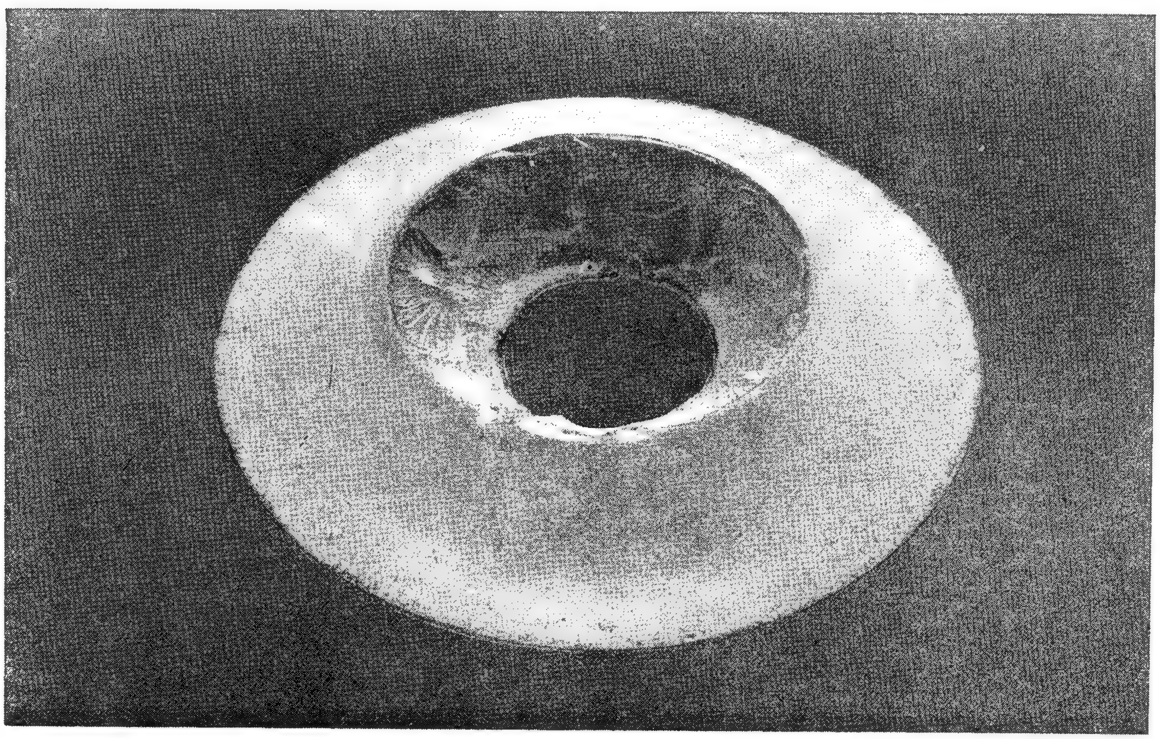


Figure B-19. Failed 1-inch-diameter, 120°, 0.25 t/D ratio window, low-pressure face.

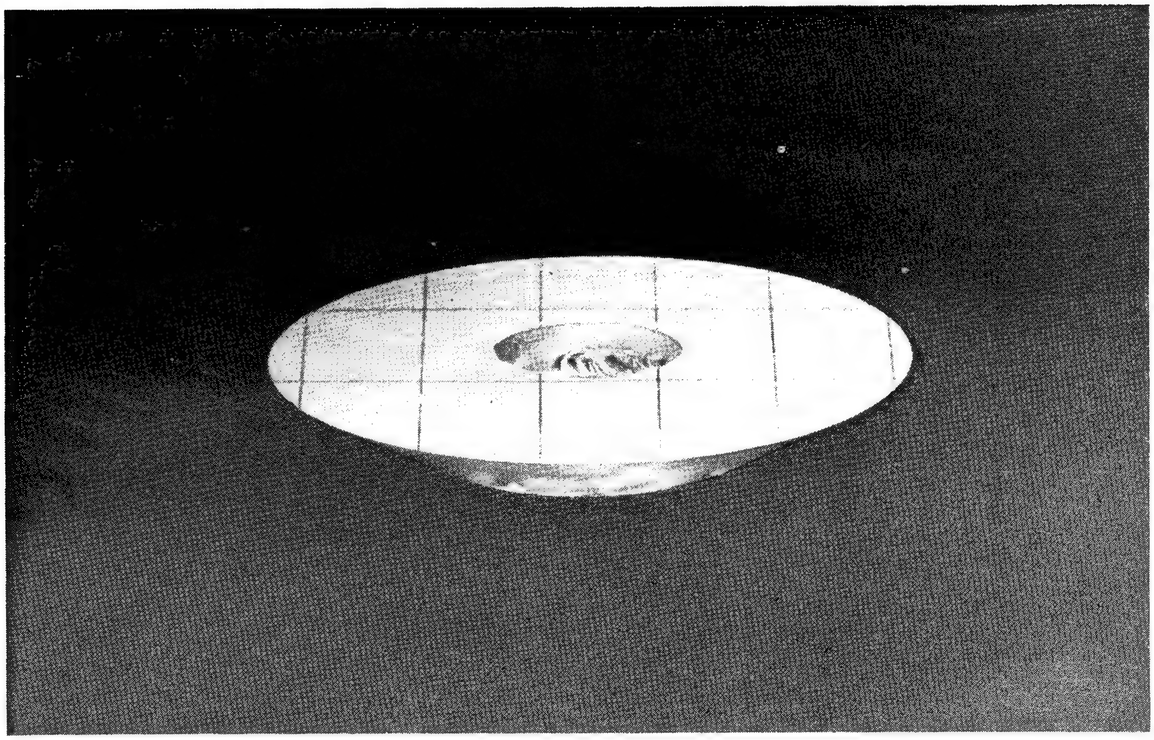


Figure B-20. Failed 1-inch-diameter, 120°, 0.25 t/D ratio window, high-pressure face.

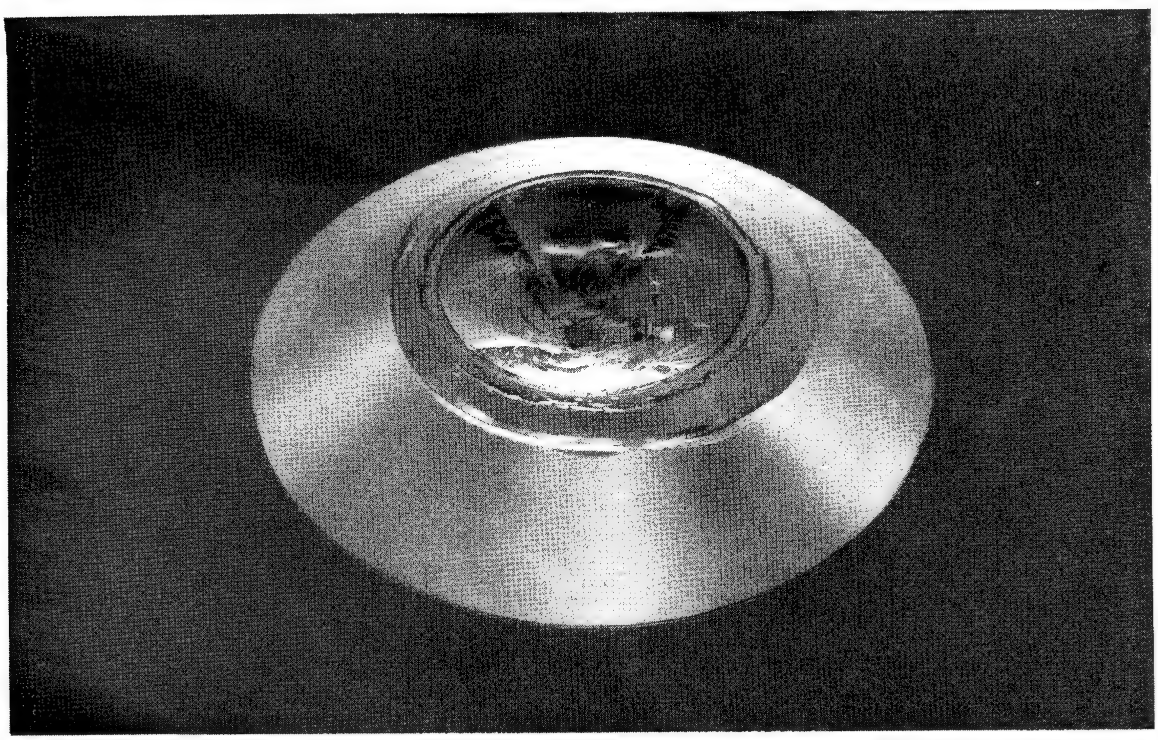


Figure B-21. Failed 1-inch-diameter, 120°, 0.375 t/D ratio window, low-pressure face.

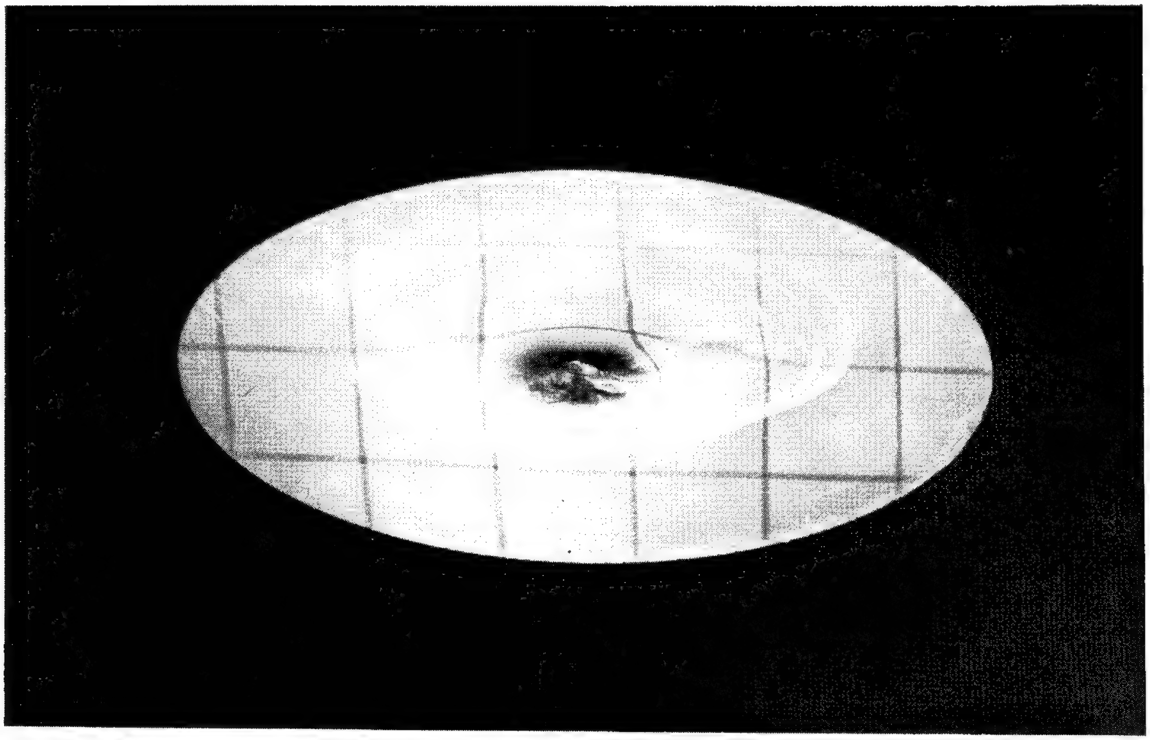


Figure B-22. Failed 1-inch-diameter, 120°, 0.375 t/D ratio window, high-pressure face.

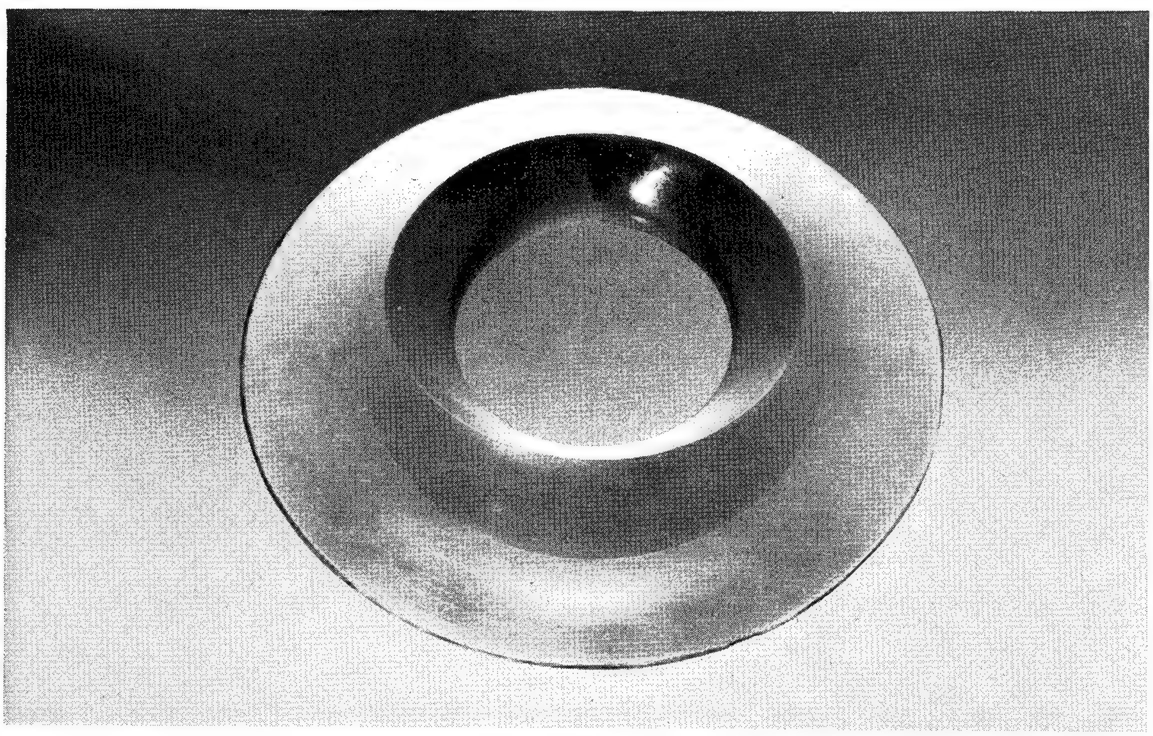


Figure B-23. Failed 1-inch-diameter, 120°, 0.625 t/D ratio window, low-pressure face.

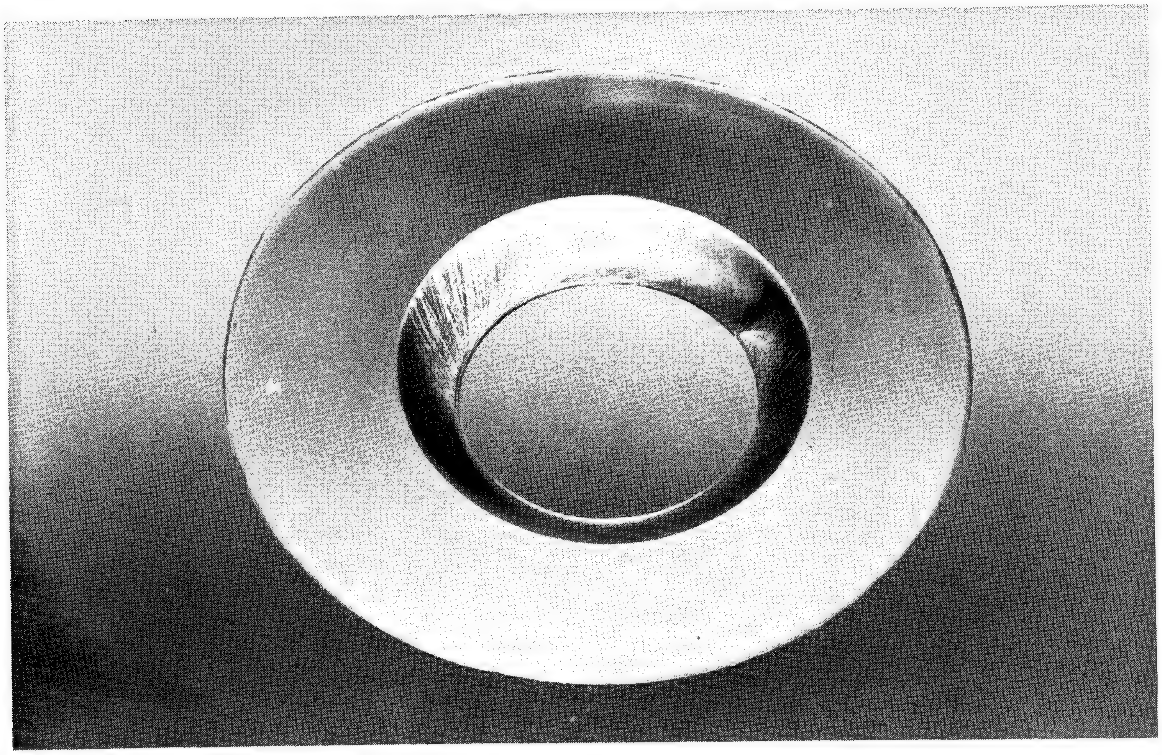


Figure B-24. Failed 1-inch-diameter, 120°, 0.625 t/D ratio window, high-pressure face.

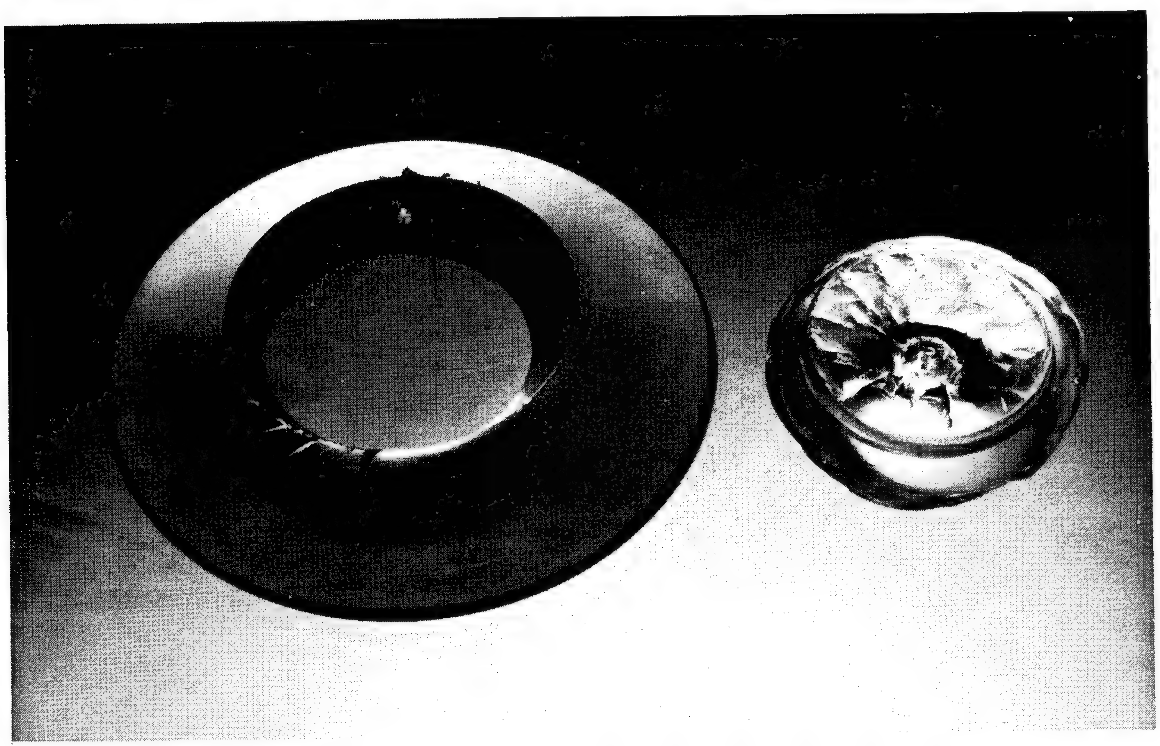


Figure B-25. Failed 1-inch-diameter, 120°, 0.5 t/D ratio window, low-pressure face, with center portion alongside.

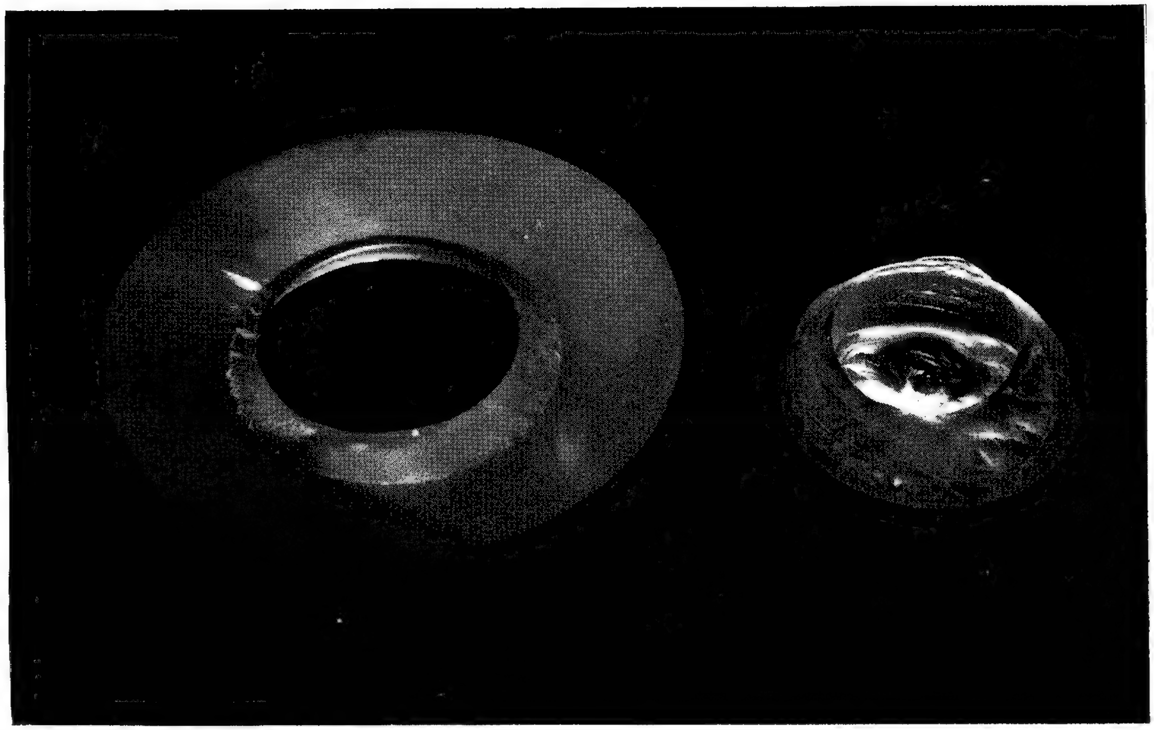


Figure B-26. Failed 1-inch-diameter, 120°, 0.5 t/D ratio window, high-pressure face, with center portion alongside.

From inspection of the retrieved window center portion, and of the outer ring-shaped fragment, as well as other windows whose testing was terminated before ejection, it can be postulated that cracks in the 120° windows were initiated at three locations. The one where cracks first appeared, at approximately 70% of critical pressure, was below the shape-transition zone on the bearing surface of the window (Figures B-27 and B-28). The cracks initiated here were continuous around the circumference of the window, and propagated themselves into the interior of the window body at approximately right angles to the conical surface.

The second location of crack initiation lay on the high-pressure face of the window. The cracks appeared here later than at the shape-transition zone and were not as continuous as those in the first location. The cracks on the high-pressure face were generated on the periphery of the cold-flow crater, which became noticeable in the 120° conical windows only at hydrostatic pressures in excess of 70% of the window critical pressure (Figure B-29).

The third location where cracks were generated was around the circumference of the low-pressure face. These cracks appear only after those in the other locations have grown to considerable proportions. It can be shown that the cracks on the low-pressure face had not yet developed (Figures B-30 and B-31) in windows with $0.5 \leq t/D \leq 0.625$ ratios at approximately 90% of the window critical pressure. Therefore, they must appear at pressures higher than 90% of critical pressure.

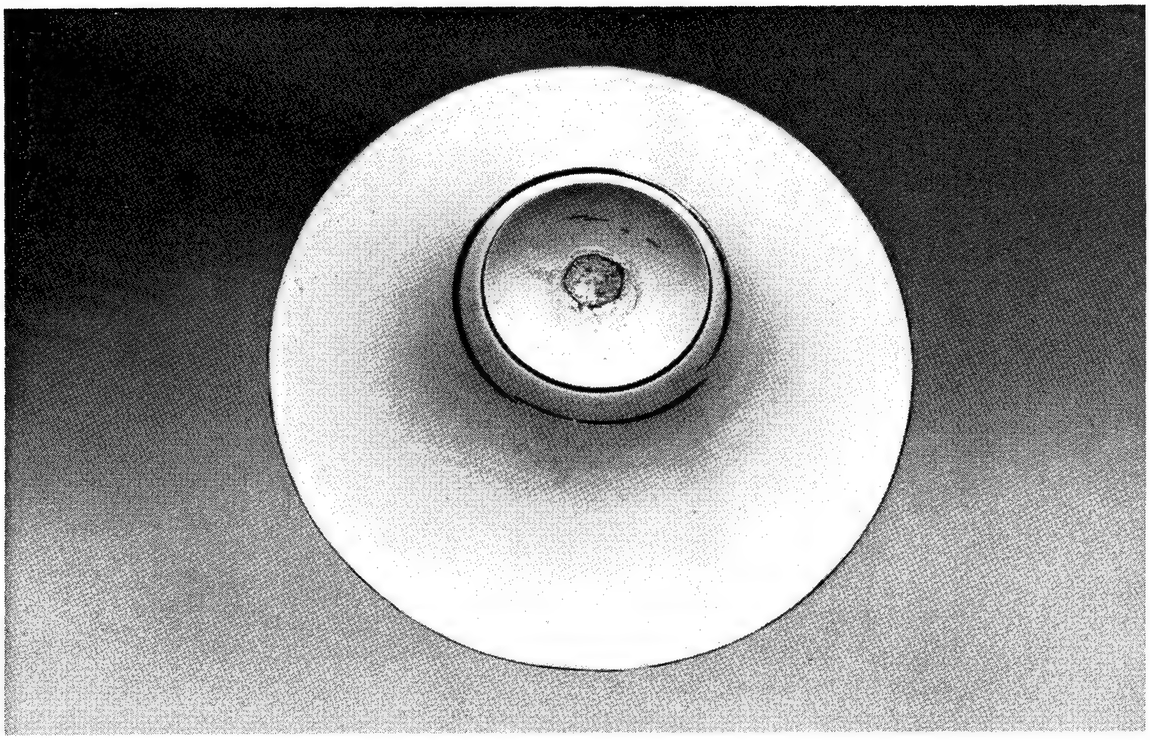


Figure B-27. Arrested failure of 1-inch-diameter, 120°, 0.625 t/D ratio window at 22, 500 psi, low-pressure face.

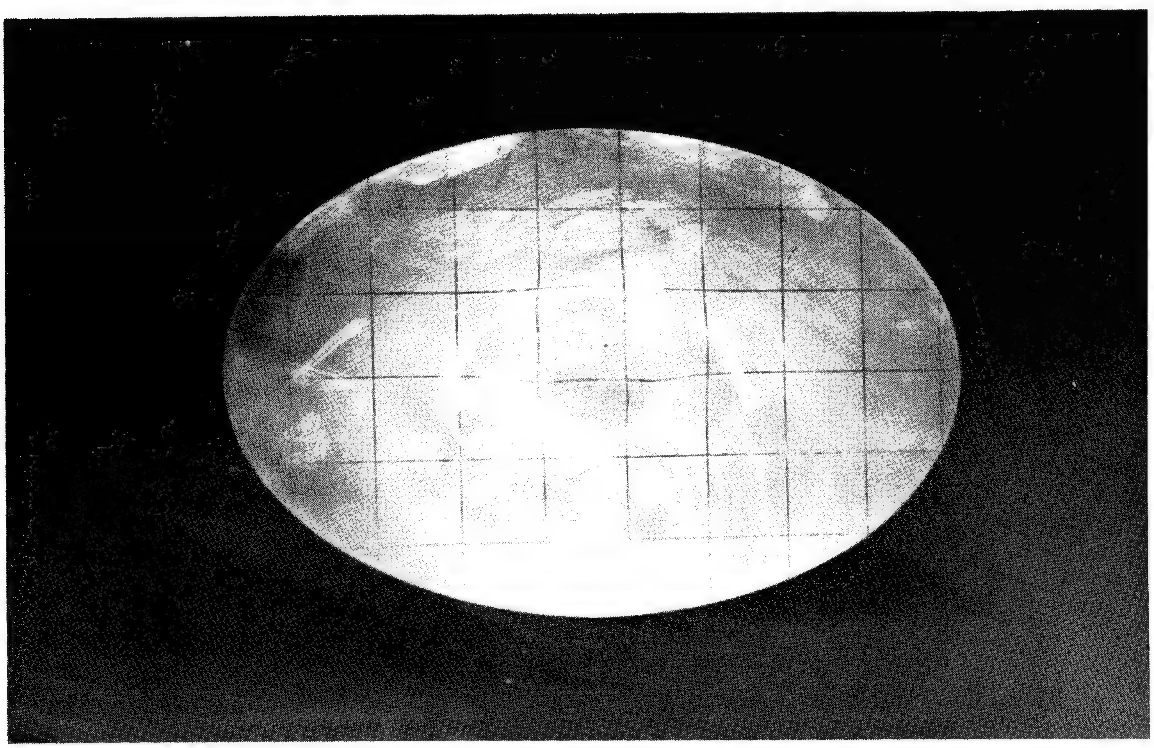


Figure B-28. Arrested failure of 1-inch-diameter, 120°, 0.625 t/D ratio window at 22, 500 psi, high-pressure face.

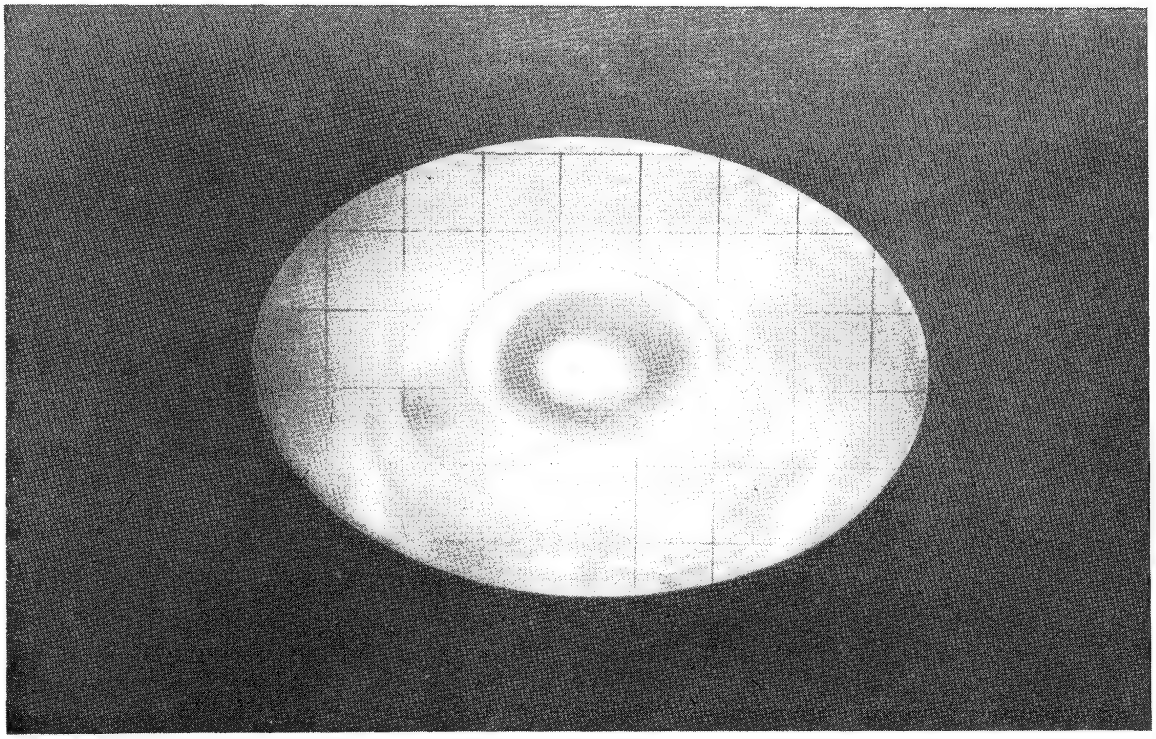


Figure B-29. Arrested failure of 1-inch-diameter, 120°, 0.625 t/D ratio window at 26, 000 psi, high-pressure face.

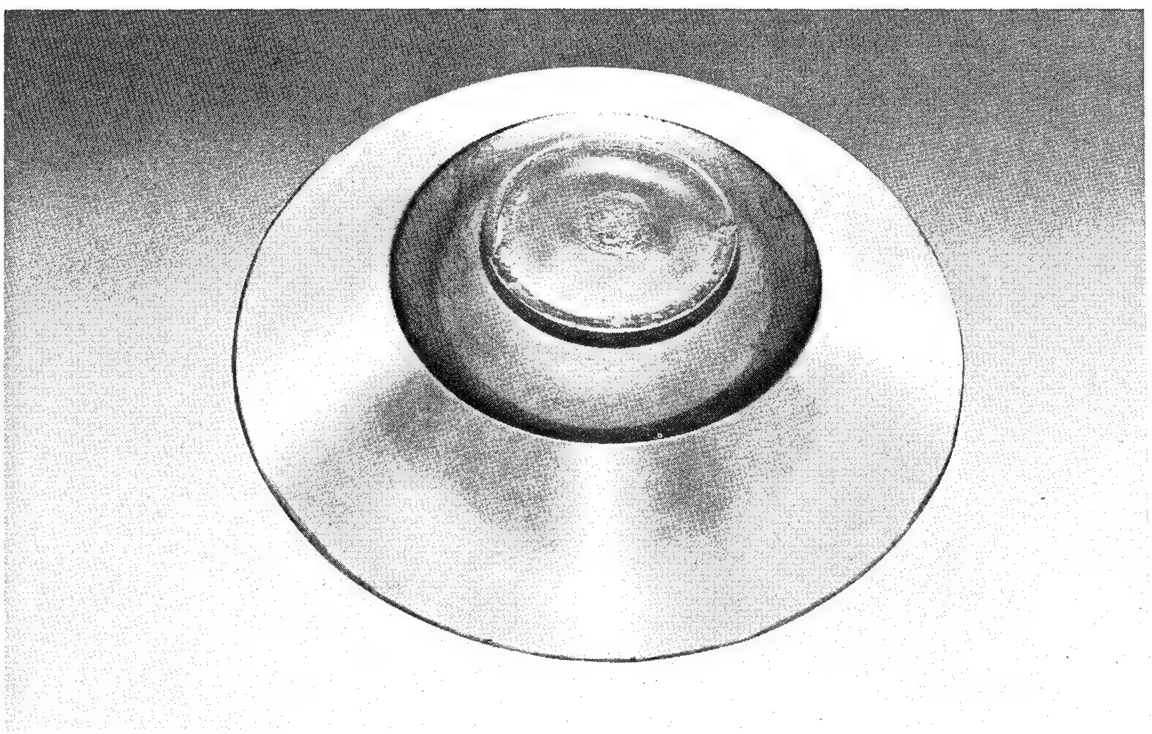


Figure B-30. Arrested failure of 1-inch-diameter, 120°, 0.625 t/D ratio window at 26, 000 psi, low-pressure face.

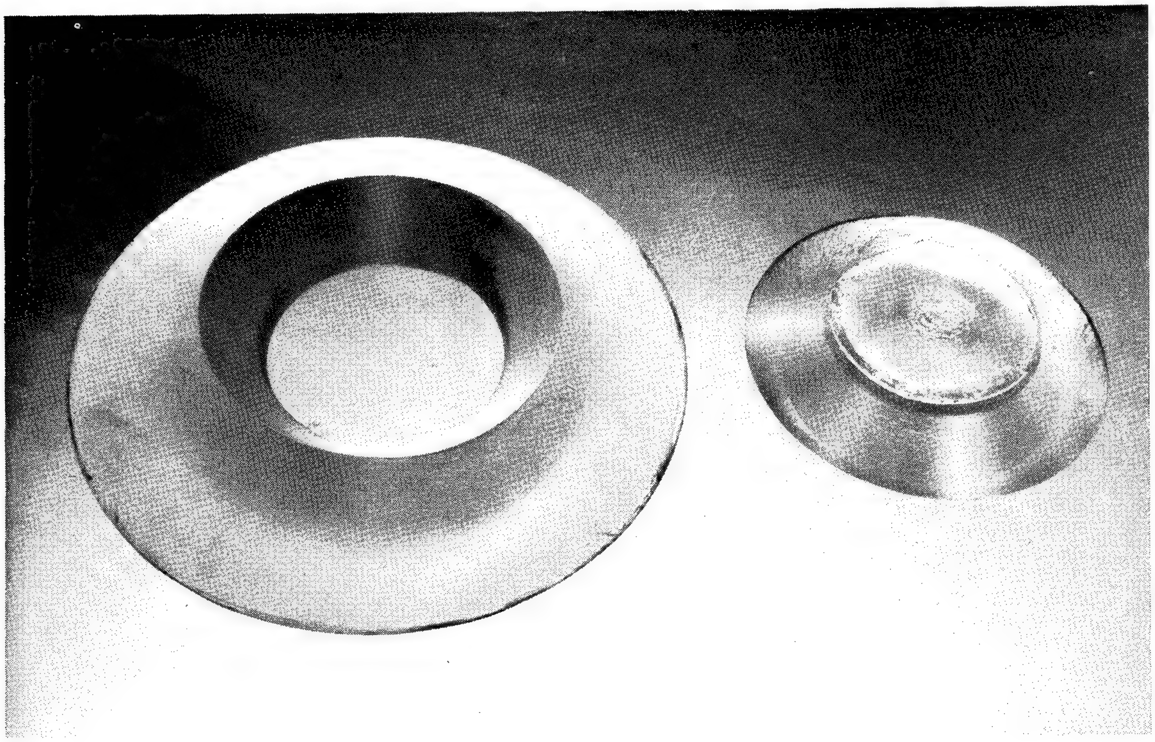


Figure B-31. Arrested failure of 1-inch-diameter, 120°, 0.625 t/D ratio window at 26, 000 psi, low-pressure face, with center portion alongside.

The 1-inch-diameter, 150° conical windows failed essentially in the same manner as the 120° windows, by ejection of the center portion, except that the center portions of the 0. 125 t/D ratio windows were not ejected when the window critical pressure was reached. The reason for this failure to eject was that upon propagation of cracks in the window (Figures B-32 and B-33) at critical pressure, the center of the window deflected into the flange cylindrical opening to such an extent that the seal between the conical surface of the window and that of the flange cavity was broken, thus relieving the hydrostatic pressure in the vessel. (If the vessel had been of very large capacity, or the window in a structure submerged in the ocean, where infinite hydrostatic energy exists, the center of the 0. 125 t/D window would also have ejected, though some leakage around the conical window surface would have occurred just prior to the ejection.)

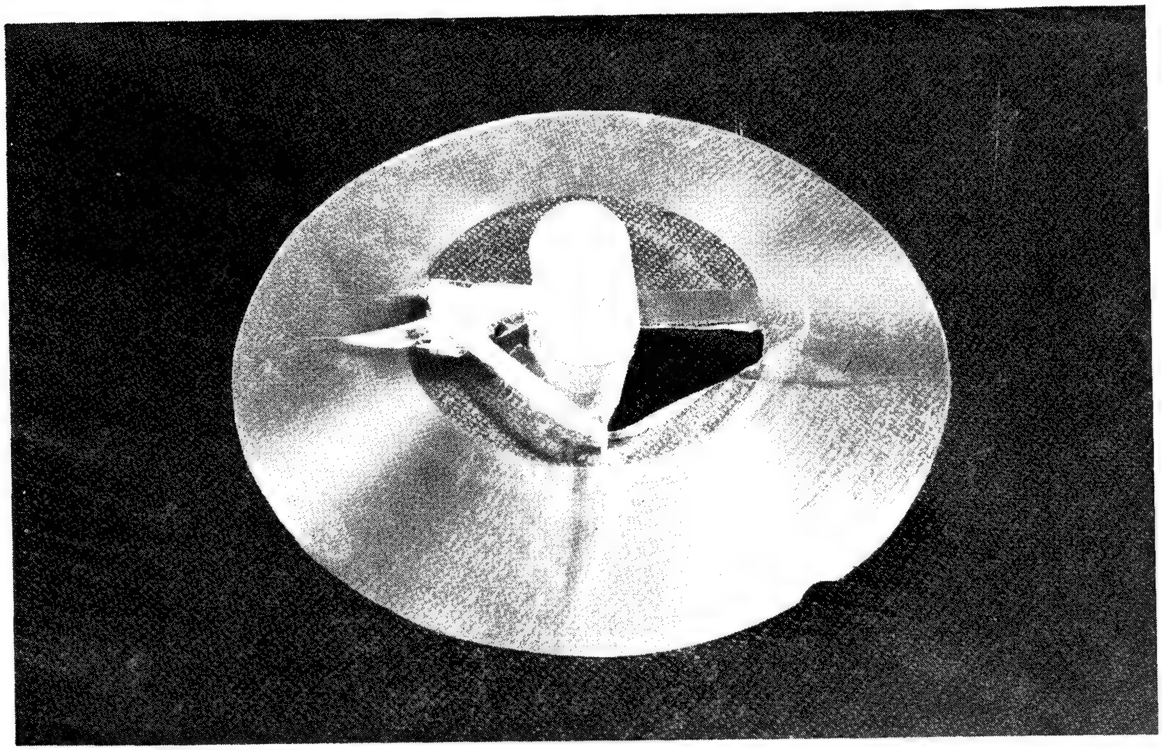


Figure B-32. Failed 1-inch-diameter, 150°, 0.125 t/D ratio window, low-pressure face, with displacement indicator anchor attached.

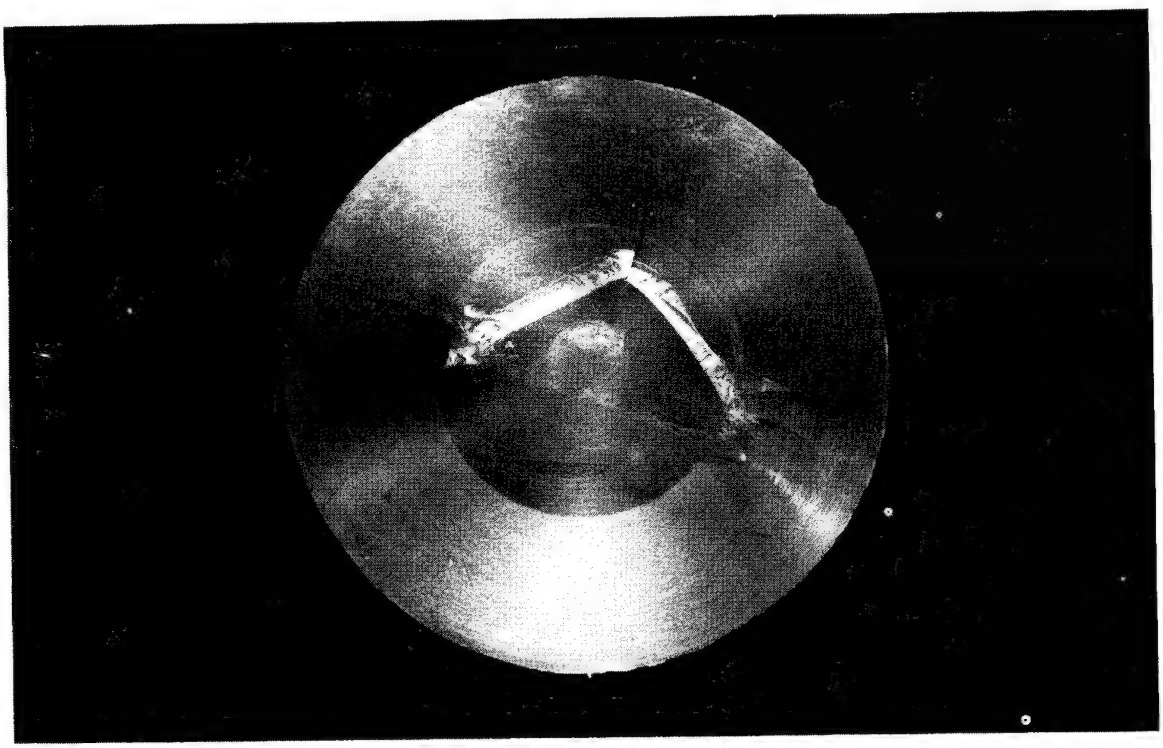


Figure B-33. Failed 1-inch-diameter, 150°, 0.125 t/D ratio window, high-pressure face.

That this was the mechanism of failure for the 0.125 t/D windows was evidenced on 0.25 t/D windows in the transition t/D range between windows whose center was ejected every time in the test, and windows whose center was not ejected because of prior leakage around the conical sealing surfaces. Thus, in 0.25 t/D windows, three different types of failure occurred. One type (Figures B-34 and B-35) was the same as for the 0.125 t/D ratio windows, where the presence of radial cracks in the center of the window permitted it to deflect to such an extent that the seal was lost between window and flange. The second type of failure for the 0.25 t/D ratio windows was a central fracture cone which originated from circumferential cracks on the window low-pressure face. This fracture cone, also previously found in 0.25 t/D windows with 60°, 90° and 120° angles, was characterized by ragged fracture surfaces, and the fact that its outside diameter was approximately 1 inch (the diameter of the window low-pressure face). The third type of failure of 0.25 t/D ratio windows was the presence of two fracture cones in the center portion of the window. The inner one was initiated by the circumferential cracks on the window low-pressure face, while the outer fracture cone started from a circumferential crack on the window bearing surface below (on the conical side) the shape-transition zone. The outer fracture cone, so typical of previously tested 120° conical windows, had a smooth cleavage surface, and its major diameter was invariably larger than the diameter of the low-pressure face.

The 150° windows with t/D ratios larger than 0.25 invariably failed by ejection of the window center portion bounded by the outer fracture cone (Figures B-36 through B-39). The inner fracture cone that started at the low-pressure face was also present in all these windows, except that it generally was not found after window failure, since it lay within the body of material ejected at critical pressure. Close inspection of a 0.625 t/D window which was loaded to only approximately 80% of its critical pressure confirmed this. In this arrested-failure specimen, three fracture cones could actually be seen (Figure B-40). The outer cone fracture had already penetrated the whole thickness of the window body, while the two inner cone fractures had penetrated only partially. The high-pressure face of the window exhibited a well-defined cold-flow crater bounded by the outer fracture cone (Figure B-41). Beyond the boundary of the outer fracture cone the high-pressure face of the window showed no traces of cold-flow cratering (Figure B-42).

Two-Inch-Diameter, 30° Conical Windows

All 2-inch-diameter, 30° conical windows failed by being ejected from the vessel. Their critical pressures were in the same pressure range as the critical pressures of 1-inch-diameter, 30° windows. The displacements for the two types of windows were different. The ratio between the displacements of the 2-inch- and the 1-inch-diameter windows was found to be roughly 2 : 1. This would seem to indicate that the displacements of 30° conical windows are proportional to their minor diameter.

Four-and-One-Half-Inch-Diameter, 60° Conical Windows

The 4.5-inch-diameter, 60° conical windows, except for the 0.25 t/D ratio specimens, were ejected completely from the mounting flange on failure. When the remains of the 4.5-inch-diameter, 0.25 t/D ratio windows (Figures B-43 and B-44), retained in the flange, were compared to the remains of 1-inch-diameter windows with the same t/D ratio, it became apparent that the mechanisms of failure must have been similar, for the appearance of the retained window fragment was the same in both cases. Since the center portion of the 4.5-inch-diameter, 0.25 t/D ratio window was not ejected from the vessel, due to premature pressure relief through a crack in that section, it was available for observation. The center portion showed deformation of both the high- and low-pressure faces. The deformation of the high-pressure face was a typical cold-flow crater, while the conical cavity on the low-pressure face was generated by fracturing of the material. The whole center portion of the window was separated from the rest of the window body by a shear cone surface. Thus, there were actually two fracture cones, the outer one which permitted the center portion of the window to separate from the ring-shaped fragment retained by the flange, and the inner one which allowed a conical cavity to be created on the low-pressure face of the window.

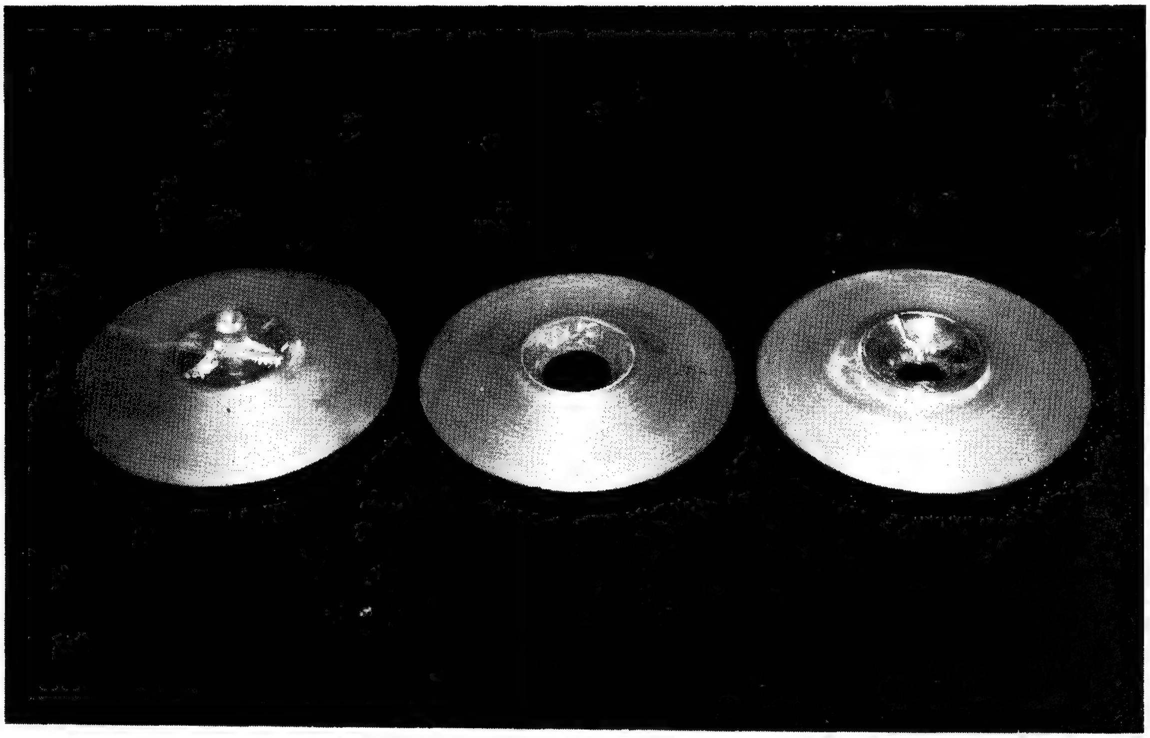


Figure B-34. Failed 1-inch-diameter, 150°, 0.25 t/D ratio windows, low-pressure faces.

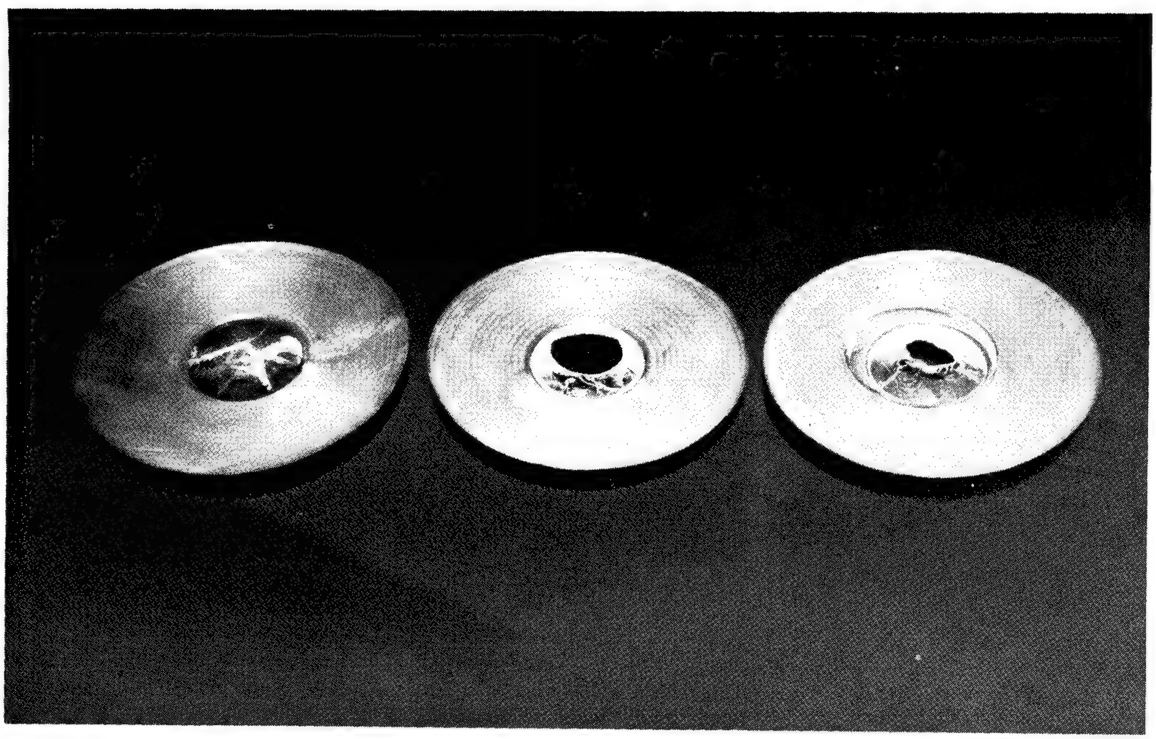


Figure B-35. Failed 1-inch-diameter, 150°, 0.25 t/D ratio windows, high-pressure faces.

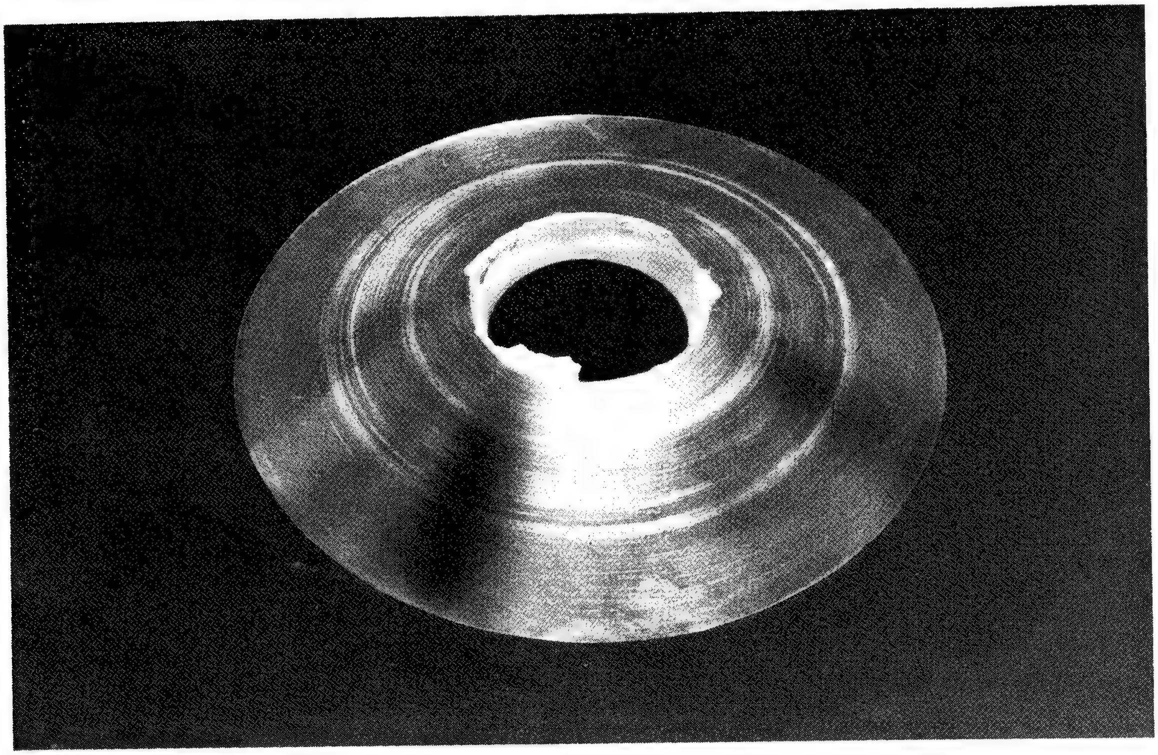


Figure B-36. Failed 1-inch-diameter, 150°, 0.5 t/D ratio window, low-pressure face.

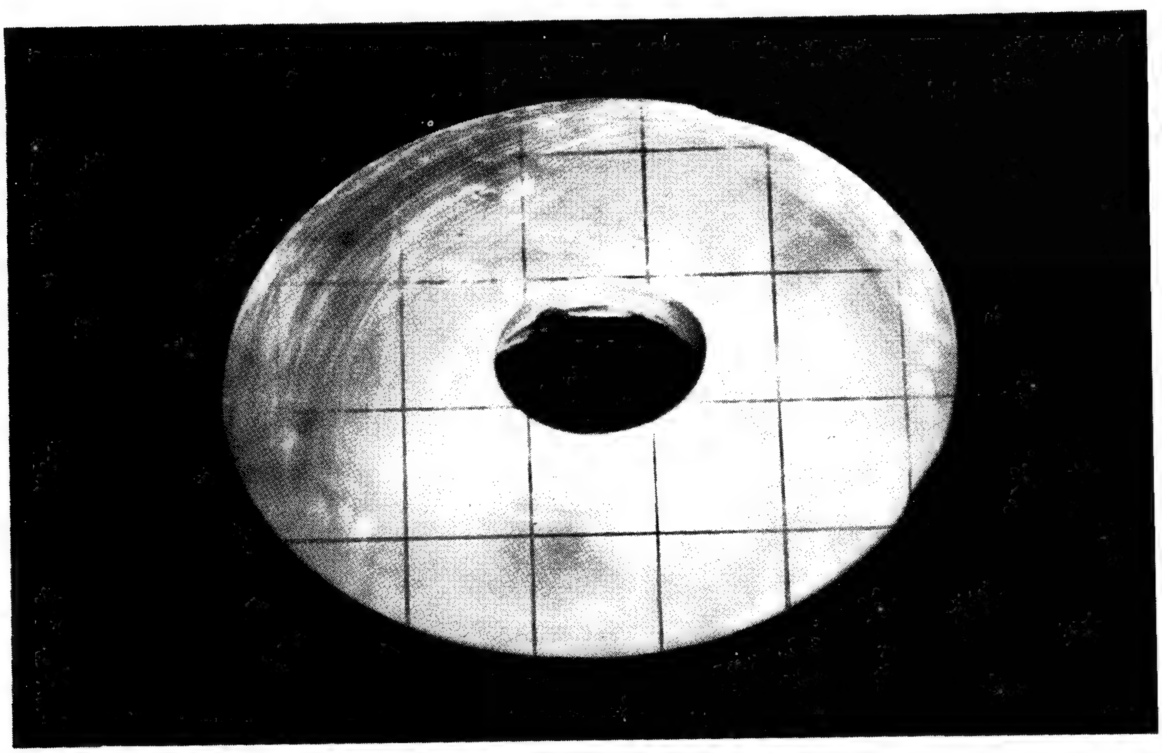


Figure B-37. Failed 1-inch-diameter, 150°, 0.5 t/D ratio window, high-pressure face.

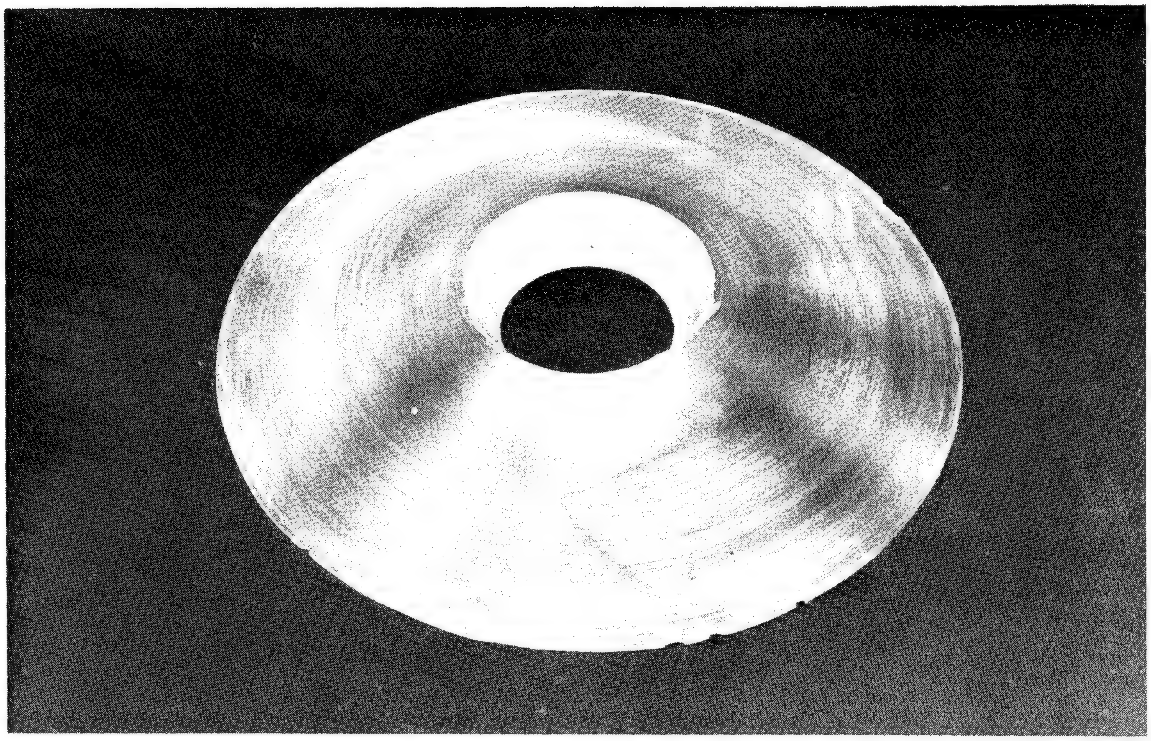


Figure B-38. Failed 1-inch-diameter, 150°, 0.625 t/D ratio window, low-pressure face.

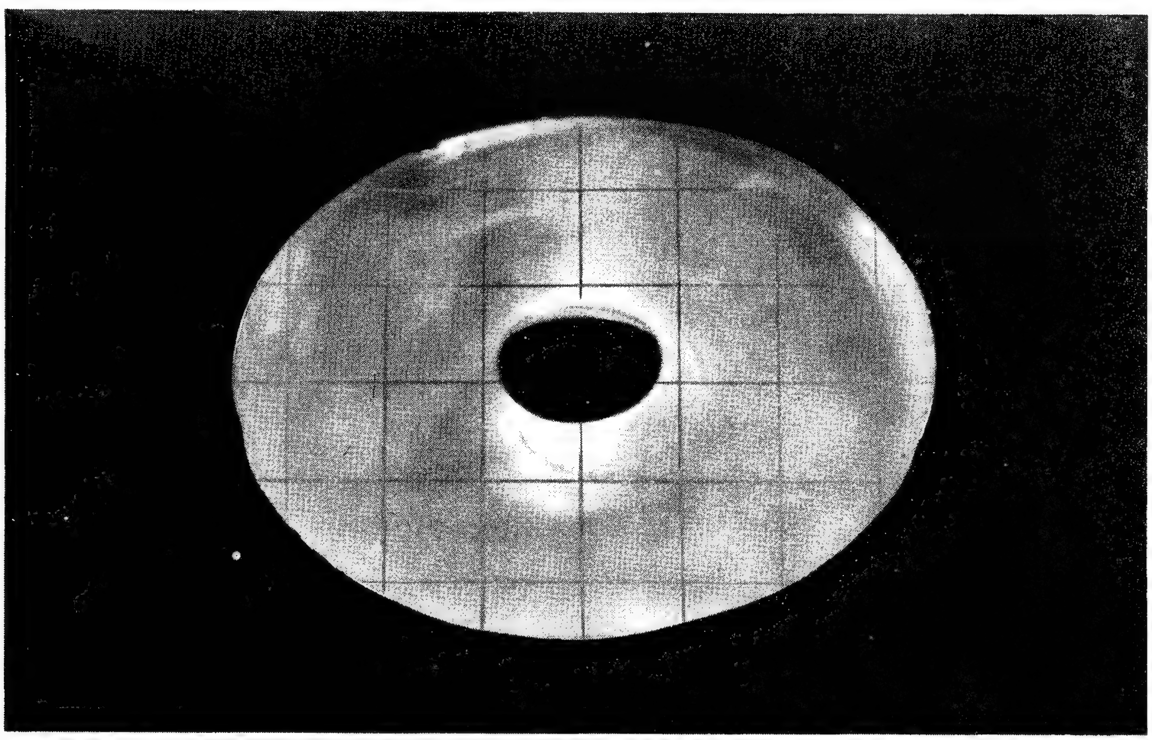


Figure B-39. Failed 1-inch-diameter, 150°, 0.625 t/D ratio window, high-pressure face.

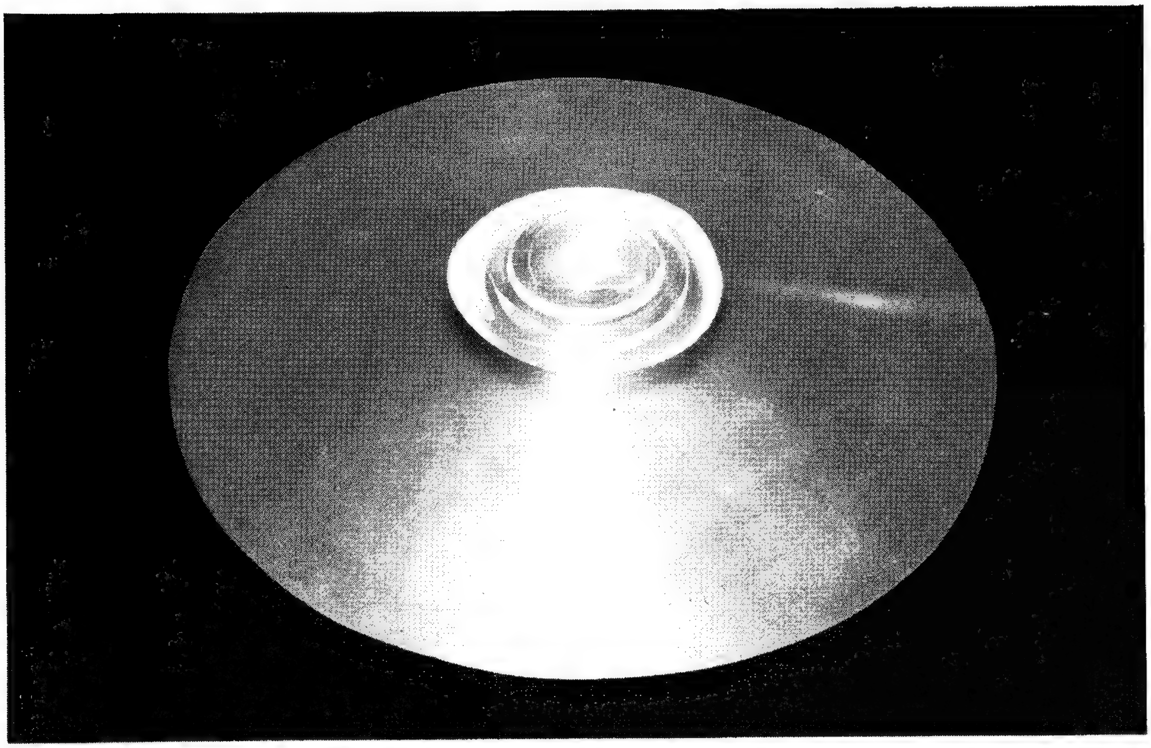


Figure B-40. Arrested failure of 1-inch-diameter, 150°, 0.625 t/D ratio window at 24, 000 psi, low-pressure face.

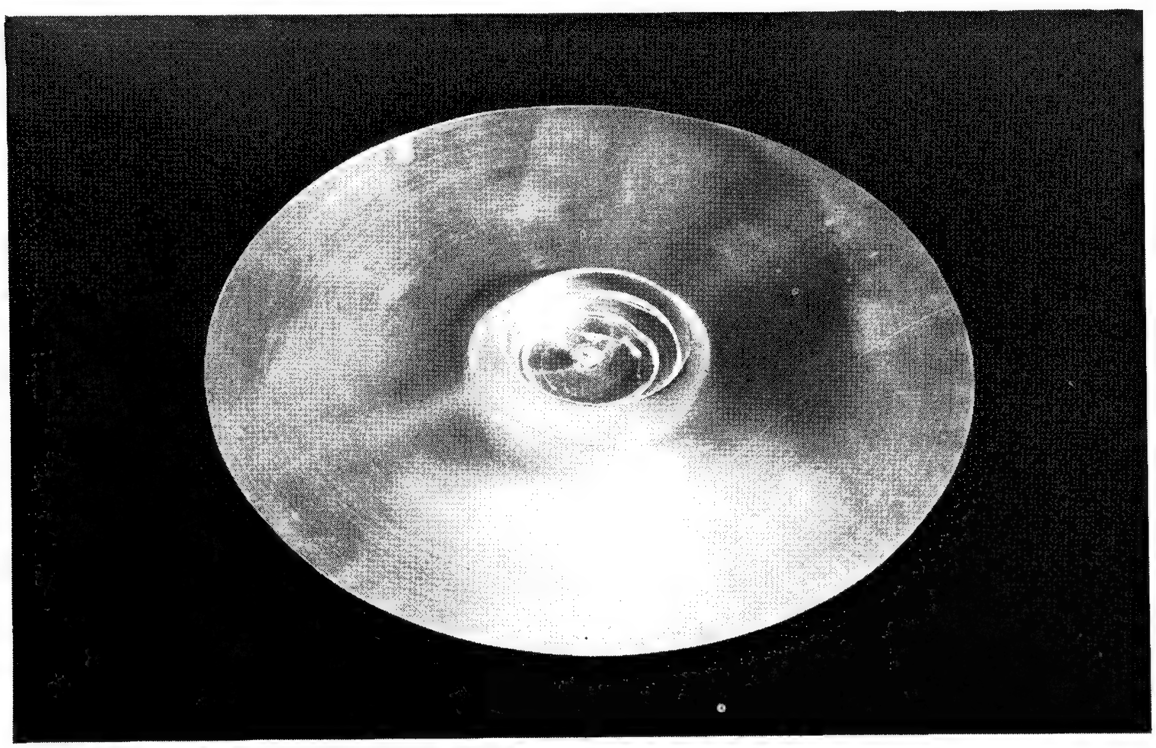


Figure B-41. Arrested failure of 1-inch-diameter, 150°, 0.625 t/D ratio window at 24, 000 psi, high-pressure face. (Cold-flow crater bounded by outer fracture cone.)

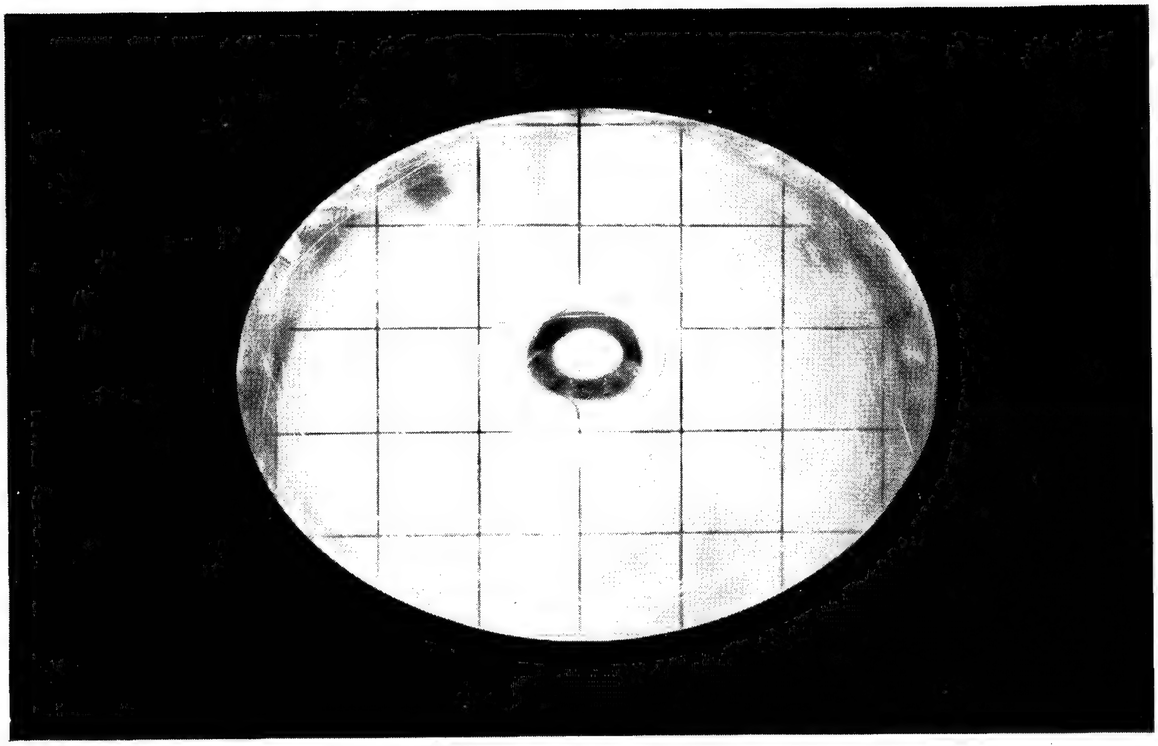


Figure B-42. Arrested failure of 1-inch-diameter, 150°, 0.625 t/D ratio window at 24,000 psi, high-pressure face. (No cold-flow crater beyond outer fracture cone.)

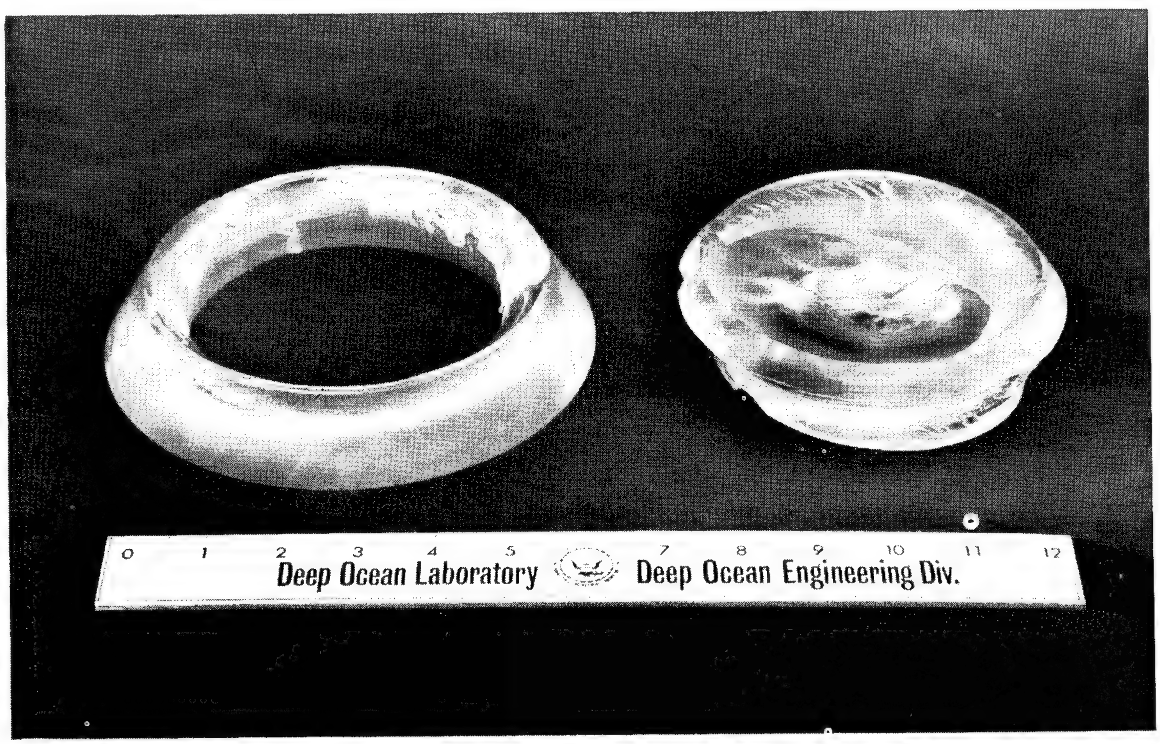


Figure B-43. Failed 4.5-inch-diameter, 60°, 0.25 t/D ratio window, low-pressure face, with center portion alongside.

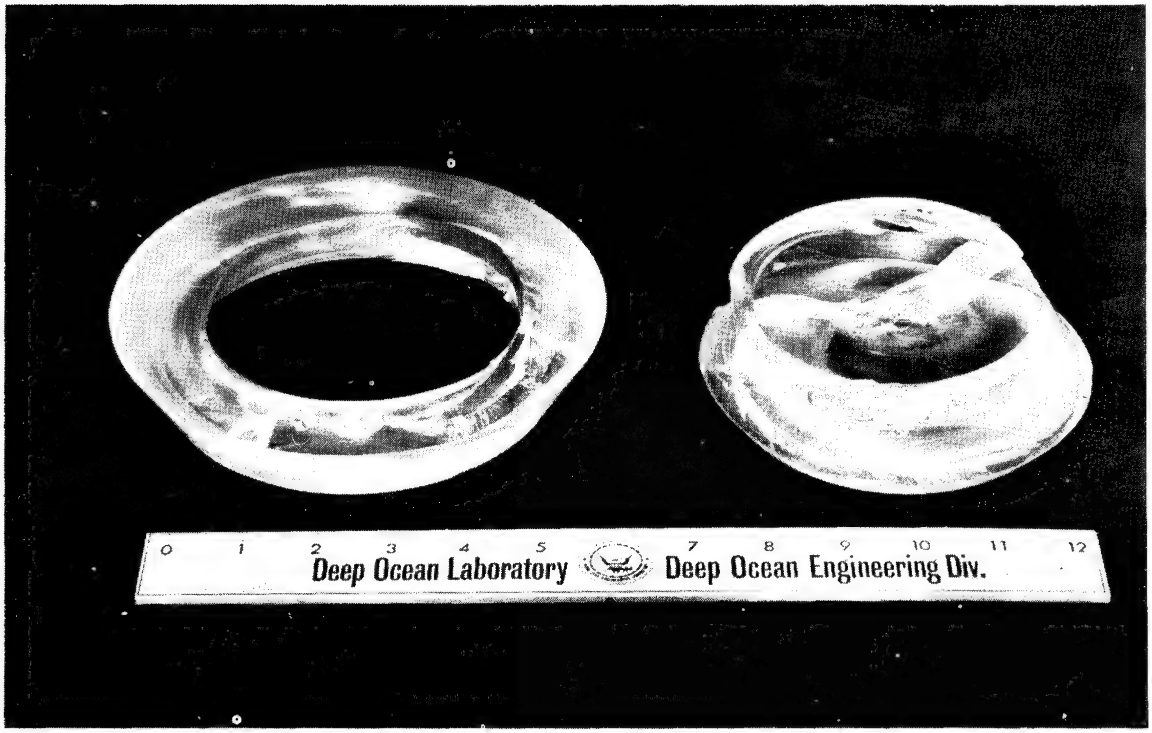


Figure B-44. Failed 4.5-inch-diameter, 60°, 0.25 t/D ratio window, high-pressure face, with center portion alongside.

Eight-Inch-Diameter, 90° Conical Windows

When the 8-inch-diameter, 4-inch-thick conical window with 90° included angle was subjected to increasing hydrostatic pressure, it failed by fracturing (Figure B-45) in a manner similar to 1-inch-diameter windows of the same t/D ratio (0.5) and included angle. The failure of the two types of windows at the same critical pressure lends considerable affirmation to the postulate that the critical pressure data obtained with 1-inch-diameter conical windows is applicable to larger conical windows provided they have the same included angle and t/D ratio.

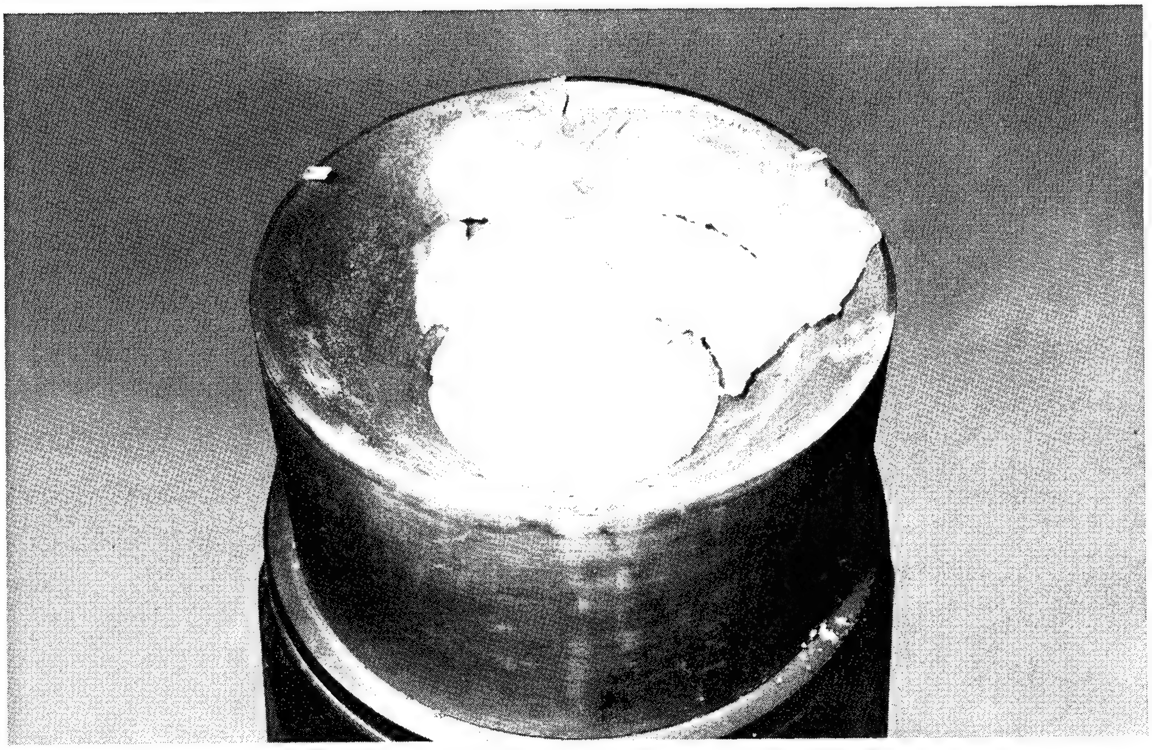


Figure B-45. Failed 8-inch-diameter, 90°, 0.5 t/D ratio window, high-pressure face, shown in mounting flange.

Appendix C

STATISTICAL EVALUATION OF THE SIZE OF THE SAMPLE GROUPS

To conduct a check as to whether the average of five experimental values is an adequate representation of the experimentally determined variable, ten specimens instead of five were tested for the 30° and 90° conical windows with a 0.5 t/D nominal ratio. The average critical pressure of the first five 30° windows tested was 8,600 psi (Table G-4, Appendix G) while that of the second five windows was 8,270 psi (Table G-5, Appendix G). When statistical methods were applied to determine the significance of the difference between the two means, it was found that the standard error of the difference was 366 psi. Since the difference between the means was 330 psi, and thus less than three standard errors of the difference for these two groups, it evidently resulted from chance and was of no significance.

The same type of analysis of experimental data derived from testing of two groups of 90° windows with five 0.5 t/D ratio windows in each (Tables G-20 and G-21, Appendix G) showed that the difference between the average critical pressures of 16,820 and 15,940 of the two groups was 880 psi, while the standard error of the difference amounted to 700 psi. This indicated that the difference between the average critical pressures of the two 90° window groups was also due solely to chance, since the difference betweeen the average critical pressures of the two groups was less than three standard errors of the difference for these two groups, and hence of no significance. Since the testing of an additional five windows of the same t/D ratio did not produce critical pressures that would be significantly different from the ones obtained by testing a single group of five windows, it can be postulated that the size of the window sample groups of same t/D ratio used in this study was sufficiently large and representative.

Appendix D

TEMPERATURE INFLUENCE EVALUATION TESTS

Besides the special tests performed on the 30° and 90° windows with a 0.5 t/D ratio to determine whether the experimental data produced by groups of five windows was repeatable, if additional groups of five were tested, tests were also performed to determine whether variation in the temperature of the mounting flange and the water adjacent to the window had significant influence on the critical pressure of the windows.

Low-temperature tests were conducted on a group of 30° windows with a 0.5 t/D ratio (Table G-6, Appendix G). The average critical pressure of the windows tested at temperatures of 35° to 40°F was higher than the average critical pressure of identical windows at 64° to 70°F in the standard temperature range (Table G-4, Appendix G) by 1,950 psi. When the standard error of the means was calculated for the critical pressures resulting from the low- and room-temperature tests, it was found to be 417 psi. Since the difference between the means of the low- and the room-temperature critical pressures was 1,950 psi, that difference was indicated as not due to chance but to some variable. Because no other additional variable was introduced into the tests other than temperature, it can be safely assumed that the difference in average critical pressures between the low- and room-temperature groups was caused by the influence of low temperature on the mechanical properties of acrylic plastic.

Appendix E

APPLICABILITY OF 1-INCH-DIAMETER WINDOW TEST DATA TO WINDOWS OF LARGER SIZES

The series of windows for the experimental validation of the t/D scaling ratio consisted of 2-inch-diameter, 30° windows with 0.125, 0.25 and 0.5 t/D ratios; 4.5-inch-diameter, 60° windows with 0.125, 0.25 and 0.5 t/D ratios; and 8-inch-diameter, 90° windows with 0.5 t/D ratios. It was reasoned that if the average critical pressures for these larger windows were approximately the same as for 1-inch-diameter windows of the same shape and t/D ratio, then the assumption that the t/D ratio is a valid scaling ratio would have been substantiated.

For the performance of critical pressure tests on the 2-inch-, 4.5-inch-, and 8-inch-diameter windows, the same experimental arrangement was followed as for the 1-inch-diameter windows except that larger mounting flanges of DOL Type I were used (Figures E-1, E-2, and E-3). Windows were fabricated again from Grade G Plexiglas to the same machining tolerances specified for the 1-inch-diameter windows. After being mounted in the appropriate flanges and subjected to the same experimental testing procedures as the 1-inch windows, the larger diameter windows were pressurized to failure.

A sufficient number of window specimens were so tested and compared in their critical pressures and displacements with 1-inch-diameter windows having the same t/D ratio and angle, that the relationship between the experimentally derived values for different window diameters could be established with reasonable confidence. The critical pressure curves (Figures 10, 12, 14, 16, 18) based on experimental data obtained with 1-inch-diameter windows were found to predict directly with reasonable accuracy the critical pressures of windows with diameters larger than 1 inch (Figures 20 and 22), provided they are composed of the same material, have the same t/D ratio and angle as the 1-inch-diameter windows, and are tested in DOL Type I mounting flanges.

The displacement curves based on experimental data derived from testing 1-inch-diameter windows (Figures 11, 13, 15, 17, and 19) do not predict directly the displacements of windows with a diameter larger than 1 inch (Figures 21 and 23). The displacements of windows with the same t/D ratio and angle but a diameter larger than 1 inch, however, are in the elastic range approximately proportional to the minor diameter of the window.

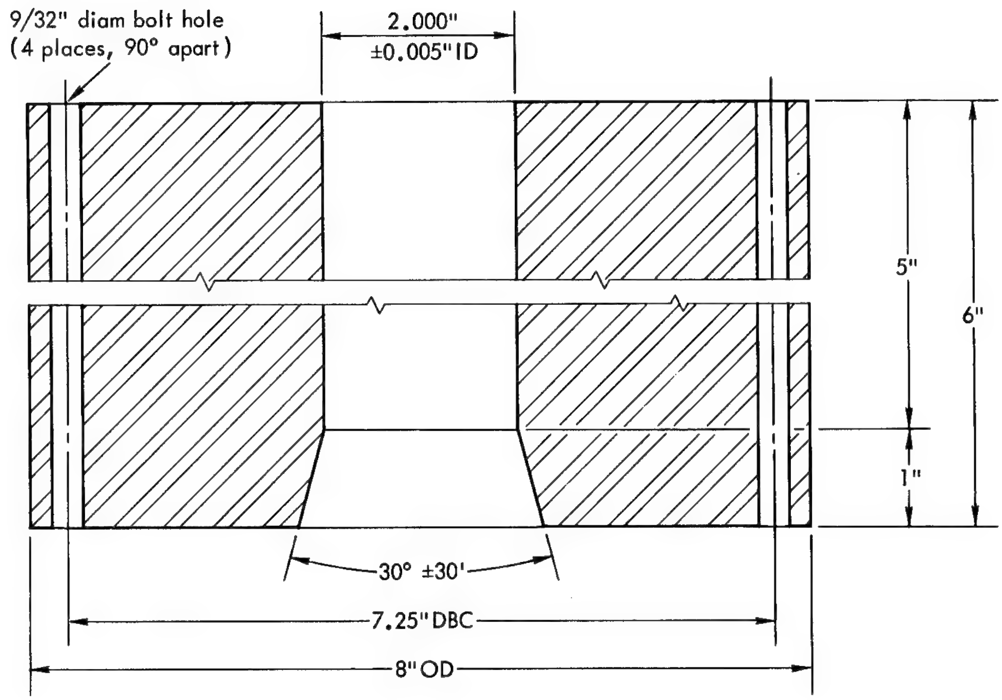


Figure E-1. DOL Type I configuration mounting flange for 2-inch-diameter, 30° conical window scaling factor validation tests.

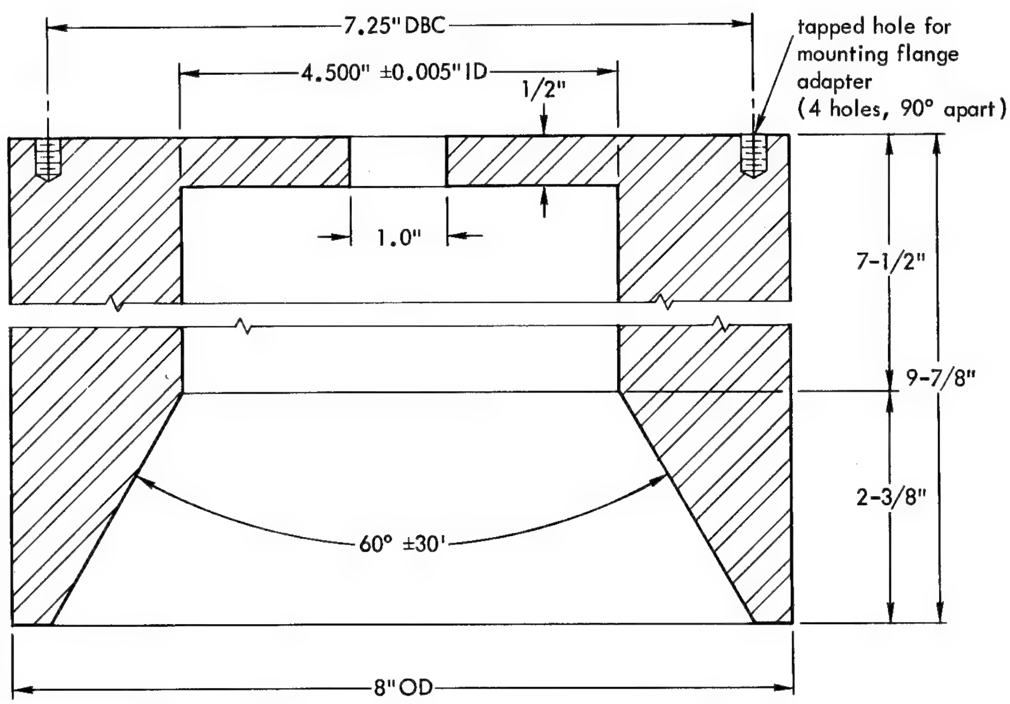


Figure E-2. DOL Type I configuration mounting flange for 4.5-inch-diameter, 60° conical window scaling factor validation tests.

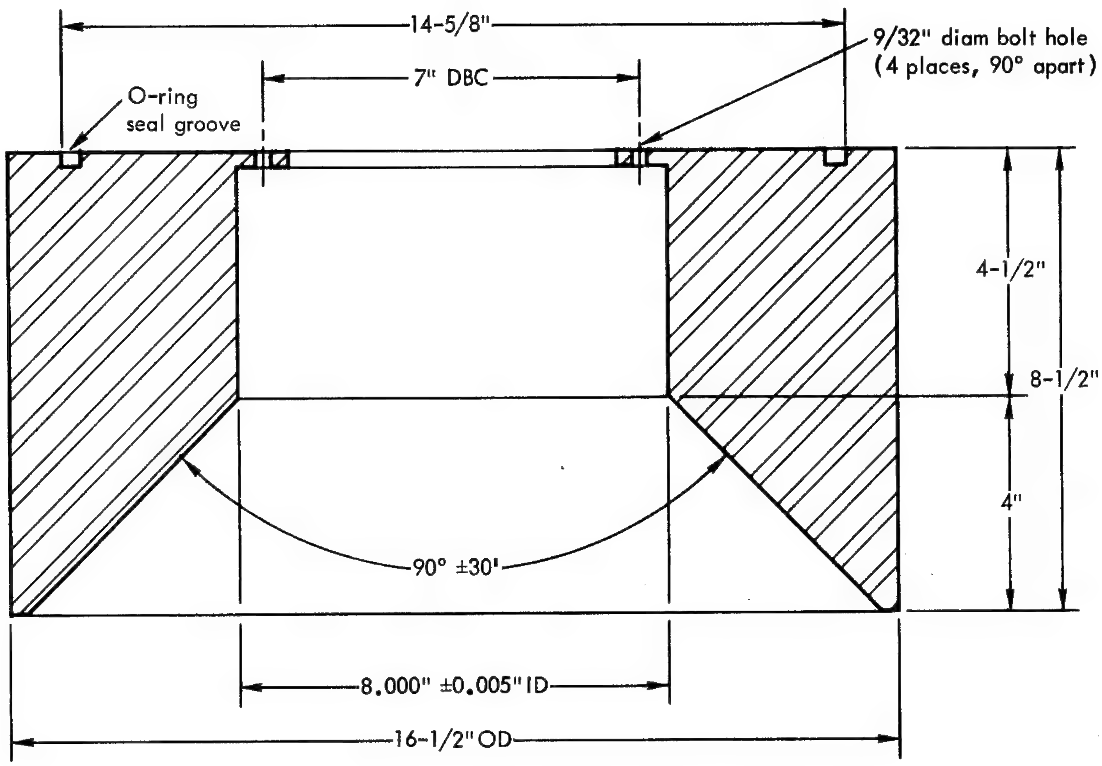


Figure E-3. DOL Type I configuration mounting flange for 8-inch-diameter, 90° conical window scaling factor validation tests.

Appendix F

EVALUATION OF OTHER WINDOW MOUNTING FLANGE CONFIGURATIONS

Since the configuration of the transition zone between the conical and the cylindrical cavities in the mounting flange may have considerable influence on the critical pressure of conical windows, several exploratory tests were conducted to determine whether a departure from the DOL Type I flange cavity configuration would influence greatly the critical pressure of conical windows under short-term hydrostatic loading. Although many flange cavity configurations are feasible for conical windows, only one in addition to the DOL Type I was utilized for exploratory investigation.

The second configuration, called DOL Type II, differed from Type I in only one vital respect. Type I was characterized by a long cylindrical cavity adjoining the conical cavity, with the same diameter as the minor diameter of the conical cavity, to provide the displaced portion of the window with radial support. In the DOL Type II configuration the cavity receiving the displaced portion was flared, with its diameter increasing beyond the juncture of the two cavities (Figure F-1). Thus, the window displaced portion was not provided with any radial support, and tended to separate from the window body retained in the flange conical cavity.

The exploratory tests conducted with 1-inch-diameter, 30° windows in a flange of the DOL Type II configuration showed that the window critical pressures were considerably lower than those obtained from testing the same windows in DOL Type I flanges. A comparison of the critical pressures of the 1-inch-diameter, 30° windows with a t/D of 1.0 in both types of flanges is as follows: DOL Type I - 27,600 psi; DOL Type II - 22,169 psi. Complete data on windows tested in DOL Type II configuration flanges are presented in Tables G-11 and G-37, Appendix G.

Since the flange configuration has such a pronounced effect on the critical pressure of the window, it is mandatory that whenever a designer wishes to apply critical pressure data from this report to a full-size window in deep submergence structure or pressure vessel, he must provide it with a DOL Type I flange. In order to achieve maximum critical pressure, the length of the cylindrical cavity in a full-size window flange must be equal to or greater than the maximum displacement that the particular window would experience prior to failure. The magnitude of the window displacements for 1-inch-diameter windows (Tables G-1 through G-10 and G-12 through G-33, Appendix G) would have to be scaled to the diameter of the window used in an actual application. The method for approximate scaling of displacements is presented in Appendix E.

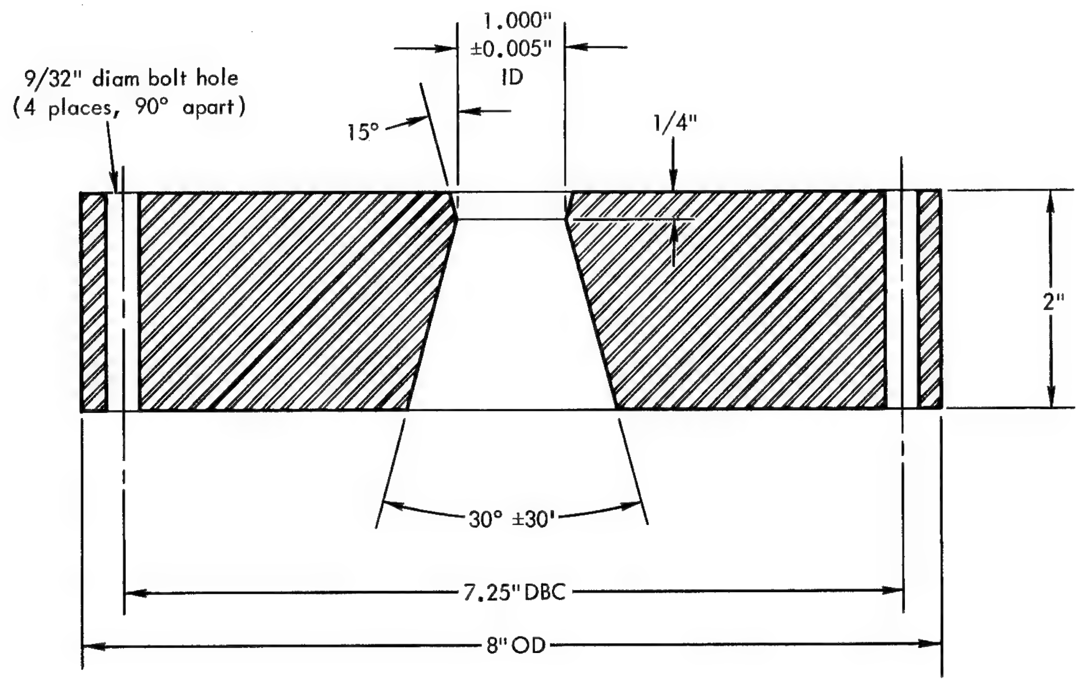


Figure F-1. DOL Type II configuration mounting flange for 1-inch-diameter, 30° conical window exploratory tests.

Appendix G

DATA FROM THE TESTING OF CONICAL ACRYLIC WINDOWS

(Tables G-1 Through G-40)

Table G-1. Test Data on 1-Inch-Diameter, 30° Windows With t/D Ratio of 0.125, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	1	2	3	4	5			
Thickness, t (in.)	0.129	0.137	0.135	0.140	0.153	0.153	0.138	0.129
Temperature (°F)	65	69	68	68	66	69	67	66
Pressurization Rate (psi/min)	750	555	500	600	800	800	642	500
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
—	←(All failed at pressures below 1,000 psi)→							
Pressure at Failure (psi)	800	850	850	750	880	850	826	750

Table G-2. Test Data on 1-Inch-Diameter, 30° Windows With t/D Ratio of 0.25 in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	6	7	8	9	10			
Thickness, t (in.)	0.250	0.253	0.250	0.250	0.251	0.253	0.251	0.250
Temperature (°F)	65	61	63	66	67	67	65	61
Pressurization Rate (psi/min)	800	680	700	740	680	800	720	680
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.009	0.011	0.009	0.011	0.012	0.009	0.010	0.012
2,000	0.020	0.025	0.025	0.030	0.030	0.020	0.026	0.030
3,000	0.042	0.050	0.050	0.054	0.053	0.042	0.050	0.054
Pressure at Failure (psi)	4,200	3,900	3,850	3,900	3,750	4,200	3,900	3,750

Table G-3. Test Data on 1-Inch-Diameter, 30° Windows With t/D Ratio of 0.375, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	11	12	13	14	15			
Thickness, t (in.)	0.344	0.348	0.340	0.338	0.340	0.348	0.342	0.338
Temperature (°F)	62	68.5	64	66	64.5	68.5	65	62
Pressurization Rate (psi/min)	560	570	630	690	650	690	615	560
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.011	0.021	0.020	0.012	0.013	0.021	0.015	0.011
2,000	0.025	0.027	0.034	0.026	0.029	0.034	0.030	0.025
3,000	0.041	0.047	0.044	0.042	0.045	0.047	0.044	0.041
4,000	0.062	0.065	0.068	0.062	0.069	0.069	0.065	0.062
5,000	0.124	0.135	0.100	0.100	0.130	0.135	0.118	0.100
Pressure at Failure (psi)	5,200	5,250	5,600	5,100	5,300	5,600	5,300	5,100

Table G-4. Test Data on 1-Inch-Diameter, 30° Windows With t/D Ratio of 0.5, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	16	17	18	19	20			
Thickness, t (in.)	0.510	0.490	0.480	0.488	0.488	0.510	0.490	0.480
Temperature (°F)	68.5	69.9	70.0	66.0	64.0	70	68	64
Pressurization Rate (psi/min)	610	620	675	780	905	975	720	610
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.005	0.005	0.006	0.005	0.005	0.006	0.005	0.005
2,000	0.015	0.011	0.014	0.010	0.010	0.015	0.012	0.010
3,000	0.028	0.020	0.019	0.015	0.015	0.028	0.020	0.015
4,000	0.040	0.031	0.034	0.020	0.020	0.040	0.031	0.020
5,000	0.053	0.044	0.055	0.034	0.029	0.055	0.042	0.029
6,000	0.072	0.060	0.073	0.058	0.045	0.073	0.060	0.045
7,000	0.092	0.079	0.095	0.130	0.070	0.130	0.093	0.070
8,000	0.116	0.110	0.135		0.120	0.135	0.120	0.110
Pressure at Failure (psi)	9,200	8,800	8,700	7,700	8,600	9,200	8,600	8,300

Table G-5. Test Data on 1-Inch-Diameter, 30° Windows With t/D Ratio of 0.5, in DOL Type I Flange: Sample Group Size Validation Tests

	Specimen Number					Maximum Value	Average Value	Minimum Value
	21	22	23	24	25			
Thickness, t (in.)	0.500	0.490	0.512	0.497	0.515	0.515	0.503	0.490
Temperature (°F)	66	70	73	72	72	73	70	66
Pressurization Rate (psi/min)	980	740	1,000	940	332	1,000	800	332
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.010	0.003	0.010	0.005	0.004	0.010	0.006	0.003
2,000	0.020	0.009	0.015	0.010	0.008	0.020	0.012	0.009
3,000	0.030	0.020	0.027	0.026	0.012	0.030	0.023	0.012
4,000	0.042	0.032	0.040	0.035	0.026	0.042	0.035	0.026
5,000	0.055	0.048	0.050	0.047	0.048	0.055	0.050	0.047
6,000	0.075	0.072	0.071	0.069	0.080	0.080	0.073	0.069
7,000	0.110	0.150	0.105	0.130	0.150	0.150	0.129	0.105
8,000					0.310			
Pressure at Failure (psi)	8,300	7,400	8,000	9,400	8,300	9,400	8,270	7,400

Table G-6. Test Data on 1-Inch Diameter, 30° Windows With t/D Ratio of 0.5, in DOL Type I Flange: Low-Temperature Tests

	Specimen Number					Maximum Value	Average Value	Minimum Value
	26	27	28	29	30			
Thickness, t (in.)	0.512	0.494	0.498	0.489	0.514	0.514	0.501	0.489
Temperature (°F)	38	36	35	40	40	40	38	35
Pressurization Rate (psi/min)	625	500	600	713	653	713	619	500
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.006	0.005	0.006	0.010	0.005	0.010	0.006	0.005
2,000	0.009	0.015	0.016	0.015	0.008	0.016	0.013	0.008
3,000	0.014	0.019	0.025	0.020	0.014	0.025	0.018	0.014
4,000	0.022	0.031	0.039	0.030	0.030	0.039	0.030	0.022
5,000	0.041	0.039	0.050	0.040	0.035	0.050	0.041	0.035
6,000	0.045	0.048	0.057	0.050	0.054	0.057	0.051	0.045
7,000	0.060	0.060	0.075	0.070	0.075	0.075	0.068	0.060
8,000	0.081	0.083	0.090	0.090	0.080	0.090	0.085	0.080
9,000	0.117	0.108	0.112	0.125	0.095	0.125	0.112	0.095
10,000	0.250	0.110	0.148	0.250	0.130	0.250	0.178	0.110
11,000			0.200					
12,000			0.350					
Pressure at Failure (psi)	10,000	10,600	12,200	10,200	9,800	12,200	10,550	9,800

Table G-7. Test Data on 1-Inch-Diameter, 30° Windows With t/D Ratio of 0.625, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	31	32	33	34	35			
Thickness, t (in.)	0.624	0.632	0.627	0.630	0.625	0.632	0.628	0.624
Temperature (°F)	67	67	67	66	62	67	65	62
Pressurization Rate (psi/min)	650	665	700	590	630	705	650	590
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.015	0.008	0.012	0.011	0.018	0.018	0.013	0.008
2,000	0.024	0.012	0.021	0.022	0.026	0.026	0.021	0.012
3,000	0.032	0.020	0.030	0.031	0.036	0.036	0.030	0.020
4,000	0.043	0.028	0.039	0.040	0.047	0.047	0.039	0.028
5,000	0.052	0.040	0.049	0.049	0.054	0.054	0.049	0.040
6,000	0.063	0.046	0.058	0.060	0.065	0.065	0.058	0.046
7,000	0.077	0.058	0.069	0.072	0.076	0.077	0.070	0.058
8,000	0.092	0.070	0.082	0.087	0.090	0.092	0.084	0.070
9,000	0.110	0.088	0.098	0.104	0.104	0.104	0.098	0.088
10,000	0.140	0.106	0.118	0.130	0.123	0.140	0.123	0.106
11,000	0.175	0.121	0.145	0.162	0.150	0.162	0.151	0.121
12,000	0.235	0.165	0.183	0.205	0.189	0.235	0.195	0.165
13,000	0.355	0.221	0.235	0.280	0.250	0.355	0.269	0.221
14,000		0.340	0.340	0.370	0.380	0.380	0.357	0.340
Pressure at Failure (psi)	13,800	14,800	14,900	15,300	14,900	15,300	14,700	13,800

Table G-8. Test Data on 1-Inch-Diameter, 30° Windows with t/D ratio of 0.75, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	36	37	38	39	40			
Thickness, t (in.)	0.727	0.726	0.721	0.740	0.730	0.740	0.728	0.726
Temperature (°F)	70	68	74	65	68	74	69	65
Pressurization Rate (psi/min)	590	635	770	740	630	770	670	630
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.003	0.005	0.007	0.015	0.011	0.003	0.008	0.015
2,000	0.008	0.011	0.015	0.025	0.021	0.008	0.016	0.025
3,000	0.014	0.016	0.018	0.033	0.030	0.014	0.022	0.033
4,000	0.022	0.025	0.022	0.041	0.040	0.022	0.030	0.041
5,000	0.032	0.033	0.028	0.050	0.049	0.028	0.039	0.050
6,000	0.041	0.043	0.037	0.057	0.060	0.037	0.048	0.060
7,000	0.053	0.055	0.046	0.066	0.071	0.053	0.058	0.071
8,000	0.067	0.068	0.059	0.078	0.085	0.067	0.072	0.078
9,000	0.084	0.082	0.075	0.095	0.100	0.075	0.087	0.100
10,000	0.104	0.099	0.095	0.115	0.121	0.099	0.107	0.121
11,000	0.130	0.121	0.118	0.132	0.150	0.118	0.130	0.150
12,000	0.160	0.147	0.160	0.153	0.190	0.147	0.162	0.190
13,000	0.197	0.179	0.230	0.179	0.245	0.179	0.206	0.245
14,000	0.251	0.210	0.330	0.209	0.328	0.210	0.265	0.330
15,000	0.335	0.257	0.440	0.250	0.415	0.250	0.339	0.440
Pressure at Failure (psi)	16,100	17,650	16,000	17,750	16,000	17,750	16,680	16,000

Table G-9. Test Data on 1-Inch-Diameter, 30° Windows With t/D Ratio of 0.875, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	41	42	43	44	45			
Thickness, t (in.)	0.889	0.878	0.879	0.880	0.877	0.889	0.860	0.877
Temperature (°F)	70	70	64	68	64	70	66	64
Pressurization Rate (psi/min)	935	725	642	712	696	935	742	642
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.003	0.000	0.004	0.000	0.000	0.004	0.002	0.000
2,000	0.004	0.010	0.007	0.005	0.006	0.010	0.005	0.004
3,000	0.008	0.017	0.010	0.010	0.014	0.017	0.012	0.008
4,000	0.014	0.019	0.014	0.015	0.021	0.021	0.017	0.014
5,000	0.019	0.024	0.022	0.020	0.032	0.032	0.023	0.019
6,000	0.025	0.030	0.030	0.029	0.042	0.042	0.032	0.025
7,000	0.033	0.048	0.039	0.031	0.046	0.048	0.039	0.031
8,000	0.042	0.053	0.049	0.042	0.055	0.055	0.048	0.042
9,000	0.062	0.059	0.059	0.055	0.067	0.067	0.060	0.059
10,000	0.065	0.068	0.072	0.068	0.076	0.076	0.070	0.065
11,000	0.077	0.083	0.086	0.078	0.096	0.096	0.084	0.077
12,000	0.094	0.105	0.102	0.098	0.109	0.109	0.102	0.094
13,000	0.118	0.125	0.120	0.120	0.124	0.124	0.121	0.118
14,000	0.153	0.160	0.142	0.152	0.142	0.160	0.143	0.142
15,000	0.203	0.197	0.165	0.190	0.164	0.203	0.183	0.164
16,000	0.253	0.245	0.194	0.231	0.198	0.253	0.225	0.194
17,000	0.297	0.288	0.224	0.280	0.242	0.297	0.267	0.224
18,000	0.337	0.328	0.262	0.320	0.302	0.337	0.310	0.262
19,000	0.398	0.376	0.300	0.372	0.347	0.399	0.359	0.300
20,000	0.550	0.455	0.328	0.460	0.390	0.550	0.437	0.328
21,000		0.940	0.358	0.840	0.460	0.940	0.518	0.358
Pressure at Failure (psi)	20,300	21,800	23,300	21,000	22,500	23,300	21,800	20,300

Table G-10. Test Data on 1-Inch-Diameter, 30° Windows With t/D Ratio of 1.0, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	46	47	48	49	50			
Thickness, t (in.)	0.950	0.978	0.977	0.980	0.969	0.980	0.970	0.950
Temperature (°F)	61	65	72	72	73	73	69	61
Pressurization Rate (psi/min)	500	610	715	600	640	715	613	500
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.005	0.006	0.004	0.005	0.007	0.007	0.005	0.004
2,000	0.008	0.007	0.008	0.009	0.010	0.010	0.008	0.007
3,000	0.016	0.009	0.011	0.011	0.013	0.016	0.012	0.011
4,000	0.025	0.015	0.014	0.014	0.017	0.025	0.017	0.014
5,000	0.034	0.023	0.024	0.019	0.025	0.034	0.025	0.019
6,000	0.041	0.032	0.026	0.025	0.030	0.041	0.031	0.025
7,000	0.048	0.043	0.035	0.032	0.040	0.048	0.040	0.032
8,000	0.058	0.045	0.047	0.038	0.042	0.058	0.046	0.038
9,000	0.069	0.056	0.061	0.047	0.054	0.069	0.057	0.047
10,000	0.083	0.066	0.071	0.057	0.062	0.083	0.068	0.057
11,000	0.097	0.079	0.088	0.066	0.080	0.097	0.082	0.066
12,000	0.107	0.100	0.105	0.077	0.096	0.107	0.097	0.090
13,000	0.117	0.116	0.116	0.090	0.115	0.117	0.110	0.096
14,000	0.128	0.133	0.137	0.104	0.125	0.137	0.125	0.104
15,000	0.138	0.159	0.151	0.117	0.140	0.159	0.141	0.117
16,000	0.154	0.193	0.174	0.134	0.180	0.193	0.167	0.134
17,000	0.169	0.218	0.195	0.150	0.198	0.218	0.186	0.150
18,000	0.187	0.253	0.211	0.176	0.238	0.253	0.213	0.176
19,000	0.207	0.290	0.236	0.203	0.247	0.290	0.236	0.203
20,000	0.231	0.307	0.257	0.232	0.300	0.307	0.265	0.232
21,000	0.263	0.325	0.293	0.263	0.310	0.325	0.291	0.263
22,000	0.302	0.340	0.307	0.300	0.331	0.340	0.316	0.300
23,000	0.360	0.363	0.364	0.321	0.358	0.364	0.353	0.321
24,000	0.463	0.398	0.490	0.345	0.400	0.490	0.419	0.345
25,000	0.515	0.466	0.520	0.480	0.471	0.520	0.490	0.466
26,000	0.548		0.570	0.550	0.562	0.570	0.557	0.548
27,000	0.640		0.670	0.650	0.660	0.670	0.655	0.640
Pressure at Failure (psi)	29,100	26,100	27,600	28,200	27,000	29,100	27,600	26,100

Table G-11. Test Data on 1-Inch-Diameter, 30° Windows With t/D Ratio of 1.00, in DOL Type II Flange: Exploratory Tests

	Specimen Number					Maximum Value	Average Value	Minimum Value
	51	52	53	54	55			
Thickness, t (in.)	0.969	0.960	0.964	0.962	0.969	0.969	0.964	0.960
Temperature (°F)	64	65	65	65		65	65	64
Pressurization Rate (psi/min)	791	741	656	783		791	743	656
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.001	0.002	0.001	0.002		0.002	0.002	0.001
2,000	0.009	0.011	0.009	0.010		0.001	0.008	0.009
3,000	0.016	0.016	0.017	0.016		0.017	0.016	0.016
4,000	0.019	0.022	0.024	0.023		0.024	0.022	0.019
5,000	0.027	0.030	0.030	0.030		0.030	0.029	0.027
6,000	0.040	0.036	0.037	0.036		0.040	0.037	0.036
7,000	0.049	0.044	0.044	0.042		0.049	0.045	0.042
8,000	0.057	0.050	0.053	0.051		0.057	0.053	0.050
9,000	0.068	0.062	0.062	0.060		0.068	0.063	0.060
10,000	0.079	0.069	0.070	0.069		0.079	0.072	0.069
11,000	0.093	0.078	0.082	0.080		0.093	0.083	0.078
12,000	0.108	0.089	0.095	0.091		0.108	0.096	0.089
13,000	0.125	0.099	0.107	0.103		0.125	0.109	0.099
14,000	0.144	0.110	0.125	0.112		0.144	0.123	0.110
15,000	0.165	0.122	0.141	0.130		0.165	0.140	0.122
16,000	0.194	0.136	0.158	0.146		0.194	0.159	0.136
17,000	0.223	0.152	0.181	0.162		0.223	0.180	0.162
18,000	0.280	0.172	0.204	0.180		0.280	0.209	0.172
19,000		0.195	0.231	0.199		0.195	0.208	0.195
20,000		0.217	0.273	0.219		0.217	0.236	0.217
21,000		0.250	0.325	0.245		0.325	0.273	0.245
22,000		0.285		0.277		0.285	0.281	0.277
23,000		0.415		0.351		0.415	0.383	0.351
Pressure at Failure (psi)	20,575	23,000	21,300	23,500		23,500	22,169	20,575

Table G-12. Test Data on 1-Inch-Diameter, 60° Windows With t/D Ratio of 0.125, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	56	57	58	50	60			
Thickness, t (in.)	0.138	0.136	0.127	0.141	0.132	0.141	0.135	0.127
Temperature (°F)	68	69	69.5	67.5	70	70	69	68
Pressurization Rate (psi/min)	581	671	750	674	635	750	662	581
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	(Failed)	0.047	0.038	0.037	0.0752	0.0752	0.049	0.037
Pressure at Failure (psi)	1,000	1,175	1,350	1,200	1,150	1,350	1,175	1,000

Table G-13. Test Data on 1-Inch-Diameter, 60° Windows With t/D Ratio of 0.25, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	61	62	63	64	65			
Thickness, t (in.)	0.246	0.247	0.245	0.247	0.246	0.247	0.246	0.245
Temperature (°F)	71	68	70	65	68	71	68	65
Pressurization Rate (psi/min)	651	645	638	630	640	651	641	630
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.004	0.0035	0.005	0.004	0.004	0.005	0.004	0.0035
2,000	0.015	0.008	0.008	0.007	0.010	0.015	0.010	0.007
3,000	0.028	0.017	0.012	0.015	0.015	0.028	0.017	0.012
4,000	0.044	0.030	0.027	0.028	0.020	0.044	0.030	0.020
5,000	0.105	0.068	0.053	0.057	0.040	0.105	0.064	0.040
Pressure at Failure (psi)	5,100	5,325	5,450	5,500	5,270	5,500	5,280	5,100

Table G-14. Test Data on 1-Inch-Diameter, 60° Windows With t/D Ratio of 0.375, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	66	67	68	69	70			
Thickness, t (in.)	0.356	0.327	0.361	0.366	0.355	0.366	0.352	0.327
Temperature (°F)	67	68	70	72	64	72	68	64
Pressurization Rate (psi/min)	664	709	665	780	633	780	690	633
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.004	0.003	0.004	0.003	0.004	0.004	0.0035	0.003
2,000	0.005	0.005	0.007	0.004	0.006	0.007	0.005	0.004
3,000	0.007	0.008	0.010	0.006	0.009	0.009	0.008	0.006
4,000	0.008	0.010	0.012	0.007	0.010	0.012	0.009	0.007
5,000	0.010	0.012	0.014	0.011	0.012	0.014	0.012	0.010
6,000	0.012	0.014	0.016	0.020	0.013	0.020	0.015	0.012
7,000	0.026	0.030	0.020	0.035	0.018	0.035	0.026	0.018
8,000	0.040	0.045	0.025	0.055	0.024	0.055	0.038	0.024
Pressure at Failure (psi)	8,800	7,800	9,150	8,850	8,500	9,150	8,620	7,800

Table G-15. Test Data on 1-Inch-Diameter, 60° Windows With t/D Ratio of 0.5, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	71	72	73	74	75			
Thickness, t (in.)	0.492	0.493	0.494	0.492	0.490	0.494	0.493	0.490
Temperature (°F)	66	69	69	69	67	69	68	66
Pressurization Rate (psi/min)	669	675	672	684	985	985	736	669
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.004	0.007	0.005	0.004	0.001	0.007	0.005	0.001
2,000	0.005	0.010	0.007	0.005	0.0025	0.010	0.006	0.0025
3,000	0.007	0.012	0.008	0.008	0.005	0.012	0.008	0.005
4,000	0.008	0.013	0.010	0.010	0.006	0.013	0.009	0.006
5,000	0.009	0.015	0.011	0.015	0.007	0.015	0.011	0.007
6,000	0.010	0.016	0.013	0.020	0.0075	0.020	0.015	0.0075
7,000	0.012	0.019	0.015	0.026	0.022	0.026	0.019	0.012
8,000	0.014	0.022	0.017	0.032	0.028	0.032	0.023	0.014
9,000	0.016	0.034	0.023	0.041	0.036	0.041	0.030	0.016
10,000	0.022	0.046	0.033	0.055	0.046	0.055	0.040	0.022
11,000	0.038	0.064	0.044	0.079	0.048	0.079	0.055	0.038
12,000	0.073	0.107	0.068	0.210	0.059	0.210	0.103	0.059
13,000	0.260		0.113		0.079	0.260	0.150	0.079
14,000			0.610		0.137	0.610	0.373	0.137
Pressure at Failure (psi)	13,350	13,000	14,450	12,600	14,750	14,750	13,650	12,600

Table G-16. Test Data on 1-Inch-Diameter, 60° Windows With t/D Ratio of 0.625, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	76	77	78	79	80			
Thickness, t (in.)	0.626	0.632	0.627	0.626	0.623	0.632	0.627	0.623
Temperature (°F)	68	70	70	65	73	73	69	65
Pressurization Rate (psi/min)	669	497	651	612	668	669	619	497
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.012	0.010	0.010	0.006	0.004	0.012	0.008	0.004
2,000	0.014	0.012	0.014	0.008	0.005	0.014	0.012	0.005
3,000	0.016	0.014	0.018	0.010	0.007	0.018	0.013	0.007
4,000	0.018	0.016	0.022	0.012	0.008	0.022	0.015	0.008
5,000	0.018	0.025	0.026	0.014	0.010	0.026	0.019	0.010
6,000	0.021	0.030	0.029	0.015	0.011	0.030	0.021	0.011
7,000	0.023	0.032	0.033	0.017	0.013	0.033	0.024	0.013
8,000	0.027	0.037	0.037	0.019	0.015	0.037	0.027	0.015
9,000	0.031	0.043	0.041	0.024	0.017	0.043	0.031	0.017
10,000	0.035	0.047	0.046	0.038	0.018	0.047	0.037	0.018
11,000	0.040	0.055	0.051	0.040	0.021	0.055	0.041	0.021
12,000	0.045	0.060	0.057	0.042	0.024	0.060	0.046	0.024
13,000	0.052	0.067	0.062	0.050	0.028	0.067	0.052	0.028
14,000	0.060	0.073	0.068	0.053	0.033	0.073	0.057	0.033
15,000	0.068	0.083	0.077	0.058	0.044	0.083	0.066	0.044
16,000	0.078	0.094	0.086	0.066	0.054	0.094	0.076	0.054
17,000	0.088	0.104	0.097	0.077	0.067	0.104	0.087	0.067
18,000	0.103	0.120	0.110	0.088	0.083	0.120	0.101	0.083
19,000	0.119	0.147	0.134	0.109	0.108	0.147	0.122	0.108
20,000	0.146	0.177	0.174	0.133	0.153	0.177	0.157	0.146
21,000	0.205	0.220	0.246	0.173	0.250	0.250	0.219	0.173
22,000	0.330	0.280	0.305	0.247	0.358	0.358	0.304	0.247
23,000	0.440	0.355	0.347	0.347	0.405	0.440	0.379	0.347
24,000	0.518	0.410	0.390	0.391	0.452	0.518	0.432	0.390
25,000		0.435	0.415	0.415		0.435	0.422	0.415
26,000		0.478	0.438	0.459		0.478	0.485	0.458
27,000				0.494		0.484	0.484	0.484
28,000				0.498		0.498	0.497	0.489
Pressure at Failure (psi)	24,850	26,600	26,400	28,100	24,500	28,100	26,090	24,500

Table G-17. Test Data on 1-Inch-Diameter, 90° Windows With t/D Ratio of 0.125, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	81	82	83	84	85			
Thickness, t (in.)	0.147	0.134	0.140	0.138	0.110	0.147	0.134	0.110
Temperature (°F)	74.3	73.4	72.5	72.5	72.5	74.3	73.2	72.5
Pressurization Rate (psi/min)	700	708	620	665	625	708	664	620
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	←(Failed below 1,000 psi)→			0.018	←(Failed below 1,000 psi)→			
Pressure at Failure (psi)	1,000	800	800	1,150	600	1,150	870	600

Table G-18. Test Data on 1-Inch-Diameter, 90° Windows With t/D Ratio of 0.25, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	86	87	88	89	90			
Thickness, t (in.)	0.260	0.258	0.248	0.255	0.254	0.260	0.255	0.248
Temperature (°F)	69.5	67.5	68.0	69.0	70.5	69.5	68.9	67.5
Pressurization Rate (psi/min)	679	658	638	675	650	679	660	638
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.005	0.003	0.003	0.007	0.002	0.007	0.004	0.002
2,000	0.014	0.006	0.006	0.010	0.005	0.014	0.008	0.005
3,000	0.022	0.012	0.008	0.013	0.010	0.022	0.013	0.008
4,000	0.031	0.022	0.012	0.017	0.024	0.031	0.021	0.012
5,000	0.073	0.034	0.022	0.022	0.050	0.073	0.040	0.022
6,000		0.067	0.095	0.060		0.095	0.074	0.060
Pressure at Failure (psi)	5,300	6,300	6,100	6,200	5,300	6,300	5,840	5,300

Figure G-19. Test Data on 1-Inch-Diameter, 90° Windows With t/D Ratio of 0.375, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	91	92	93	94	95			
Thickness, t (in.)	0.381	0.370	0.374	0.379	0.380	0.381	0.377	0.370
Temperature (°F)	75.2	71.6	76.1	75.2	73.4	76.1	74.3	71.6
Pressurization Rate (psi/min)	661	674	673	672	668	674	670	661
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.009	0.008	0.010	0.006	0.005	0.010	0.008	0.005
2,000	0.011	0.012	0.012	0.007	0.010	0.012	0.010	0.007
3,000	0.013	0.014	0.014	0.009	0.013	0.014	0.012	0.009
4,000	0.014	0.016	0.016	0.010	0.017	0.017	0.015	0.010
5,000	0.015	0.019	0.018	0.013	0.022	0.022	0.017	0.013
6,000	0.017	0.022	0.020	0.016	0.027	0.027	0.022	0.016
7,000	0.037	0.028	0.022	0.020	0.033	0.037	0.028	0.020
8,000	0.039	0.036	0.025	0.026	0.039	0.039	0.033	0.025
9,000	0.042	0.043	0.030	0.033	0.047	0.047	0.039	0.030
10,000	0.046	0.055	0.043	0.045	0.060	0.060	0.050	0.043
11,000	0.075	0.078	0.118	0.067	0.090	0.118	0.086	0.067
Pressure at Failure (psi)	11,850	12,150	11,250	11,900	11,500	12,150	11,730	11,250

Table G-20. Test Data on 1-Inch-Diameter, 90° Windows With t/D Ratio of 0.5, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	96	97	98	99	100			
Thickness, t (in.)	0.511	0.516	0.490	0.480	0.481	0.516	0.496	0.480
Temperature (°F)	71.6	68.4	65.3	63.5	69.8	71.6	67.7	63.5
Pressurization Rate (psi/min)	657	664	662	667	675	675	665	657
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.004	0.003	0.002	0.002	0.002	0.004	0.003	0.002
2,000	0.008	0.007	0.004	0.003	0.004	0.008	0.005	0.003
3,000	0.012	0.011	0.007	0.003	0.005	0.012	0.008	0.003
4,000	0.015	0.015	0.008	0.005	0.007	0.015	0.010	0.005
5,000	0.018	0.018	0.010	0.007	0.009	0.018	0.012	0.007
6,000	0.021	0.021	0.011	0.009	0.012	0.021	0.015	0.009
7,000	0.024	0.025	0.013	0.013	0.017	0.025	0.018	0.013
8,000	0.027	0.028	0.015	0.016	0.020	0.028	0.021	0.015
9,000	0.031	0.032	0.017	0.020	0.026	0.032	0.025	0.017
10,000	0.035	0.036	0.019	0.024	0.031	0.036	0.029	0.019
11,000	0.039	0.041	0.023	0.029	0.037	0.041	0.034	0.023
12,000	0.045	0.046	0.028	0.035	0.044	0.046	0.040	0.028
13,000	0.051	0.053	0.035	0.042	0.058	0.058	0.048	0.035
14,000	0.058	0.062	0.046	0.051	0.077	0.077	0.059	0.046
15,000	0.069	0.073	0.065	0.073	0.122	0.122	0.080	0.065
16,000	0.086	0.091	0.127	0.114		0.127	0.105	0.086
Pressure at Failure (psi)	17,900	17,850	16,400	16,400	15,550	17,900	16,820	15,550

Table G-21. Test Data on 1-Inch-Diameter, 90° Windows With t/D Ratio of 0.5, in DOL Type I Flange: Sample Group Size Validation Tests

	Specimen Number					Maximum Value	Average Value	Minimum Value
	101	102	103	104	105			
Thickness, t (in.)	0.496	0.490	0.512	0.482	0.515	0.515	0.499	0.482
Temperature (°F)	70	68	80	77	75	80	74	68
Pressurization Rate (psi/min)	672	634	670	672	570	570	837	634
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.002	0.003	0.007	0.011	0.006	0.011	0.006	0.002
2,000	0.003	0.005	0.008	0.015	0.007	0.015	0.007	0.003
3,000	0.004	0.006	0.009	0.018	0.009	0.018	0.009	0.004
4,000	0.007	0.007	0.010	0.024	0.015	0.024	0.011	0.007
5,000	0.015	0.009	0.011	0.028	0.019	0.028	0.016	0.009
6,000	0.018	0.010	0.012	0.031	0.022	0.031	0.018	0.010
7,000	0.021	0.011	0.013	0.036	0.027	0.036	0.021	0.011
8,000	0.025	0.014	0.014	0.039	0.030	0.039	0.024	0.014
9,000	0.030	0.016	0.018	0.046	0.034	0.046	0.028	0.016
10,000	0.035	0.020	0.020	0.053	0.039	0.053	0.032	0.020
11,000	0.041	0.026	0.023	0.062	0.044	0.062	0.038	0.023
12,000	0.048	0.033	0.031	0.076	0.051	0.076	0.046	0.031
13,000	0.058	0.043	0.040	0.110	0.060	0.110	0.060	0.040
14,000	0.075	0.067	0.056		0.071	0.075	0.065	0.056
15,000	0.107	0.110	0.073		0.090	0.110	0.090	0.073
Pressure at Failure (psi)	15,850	15,700	16,550	13,850	17,750	17,750	15,940	13,850

Table G-22. Test Data on 1-Inch-Diameter, 90° Windows With t/D Ratio of 0.625, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	106	107	108	109	110			
Thickness, t (in.)	0.626	0.632	0.633	0.631	0.631	0.633	0.631	0.626
Temperature (°F)	67.1	65.3	67.1	62.6	65.3	67.1	65.5	62.6
Pressurization Rate (psi/min)	669	702	851	934	613	934	754	613
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.003	0.002		0.003	0.004	0.004	0.003	0.002
2,000	0.007	0.004	0.001	0.005	0.007	0.007	0.005	0.001
3,000	0.010	0.005	0.002	0.006	0.010	0.010	0.007	0.002
4,000	0.013	0.006	0.016	0.007	0.013	0.016	0.011	0.006
5,000	0.015	0.007	0.016	0.008	0.016	0.016	0.012	0.007
6,000	0.018	0.008	0.017	0.009	0.019	0.019	0.014	0.008
7,000	0.020	0.009	0.017	0.011	0.022	0.022	0.016	0.009
8,000	0.023	0.010	0.018	0.012	0.024	0.024	0.017	0.010
9,000	0.025	0.013	0.022	0.013	0.027	0.027	0.020	0.013
10,000	0.029	0.025	0.025	0.014	0.031	0.031	0.025	0.014
11,000	0.031	0.026	0.027	0.015	0.033	0.033	0.026	0.015
12,000	0.035	0.026	0.031	0.017	0.036	0.036	0.029	0.017
13,000	0.038	0.027	0.035	0.018	0.040	0.040	0.032	0.018
14,000	0.042	0.027	0.038	0.019	0.043	0.043	0.034	0.019
15,000	0.045	0.028	0.042	0.021	0.047	0.047	0.037	0.021
16,000	0.049	0.047	0.047	0.022	0.051	0.051	0.043	0.022
17,000	0.053	0.049	0.052	0.024	0.055	0.055	0.047	0.024
18,000	0.058	0.050	0.058	0.025	0.061	0.061	0.050	0.025
19,000	0.063	0.051	0.065	0.026	0.066	0.066	0.054	0.026
20,000	0.070	0.072	0.071	0.028	0.071	0.072	0.062	0.028
21,000	0.078	0.074	0.080	0.030	0.077	0.080	0.068	0.030
22,000	0.089	0.076	0.090	0.058	0.087	0.090	0.080	0.058
23,000	0.099	0.097	0.107	0.061		0.107	0.091	0.061
24,000	0.108	0.118	0.127	0.065	0.120	0.127	0.108	0.065
25,000	0.120	0.140	0.154	0.069	0.133	0.154	0.123	0.069
26,000	0.140	0.186	0.192	0.083		0.192	0.150	0.083
27,000	0.176	0.248	0.287	0.105		0.287	0.204	0.105
Pressure at Failure (psi)	28,850	27,400	27,700	29,900	27,100	29,900	28,190	27,100

Table G-23. Test Data on 1-Inch-Diameter, 120° Windows With t/D Ratio of 0.125, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	111	112	113	114	115			
Thickness, t (in.)	0.120	0.120	0.121	0.120	0.120	0.121	0.120	0.120
Temperature (°F)	63.5	64	63.5	63	63	64	63.4	63
Pressurization Rate (psi/min)	329	524	429	449	372	524	421	329
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
—	←(All failed at pressures below 1,000 psi)→							
Pressure Failure (psi)	850	750	750	750	850	850	790	750

Table G-24. Test Data on 1-Inch-Diameter, 120° Windows With t/D Ratio of 0.25, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	116	117	118	119	120			
Thickness, t (in.)	0.241	0.240	0.244	0.243	0.239	0.244	0.243	0.239
Temperature (°F)	63	64	61	61	61	64	62	61
Pressurization Rate (psi/min)	705	657	642	623	651	703	655	623
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.004	0.003	0.002	0.003	0.002	0.004	0.003	0.002
2,000	0.007	0.006	0.005	0.005	0.005	0.007	0.006	0.005
3,000	0.011	0.010	0.009	0.008	0.009	0.011	0.009	0.008
4,000		0.024	0.014	0.015	0.016	0.024	0.017	0.014
Pressure at Failure (psi)	3,500	4,400	4,950	4,400	4,350	4,950	4,320	3,500

Table G-25. Test Data on 1-Inch-Diameter, 120° Windows With t/D Ratio of 0.375, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	121	122	123	124	125			
Thickness, t (in.)	0.349	0.331	0.330	0.328	0.337	0.349	0.335	0.328
Temperature (°F)	65.5	65.5	67	61.4	62.7	67	64.4	61.4
Pressurization Rate (psi/min)	716	717	833	680	674	833	724	674
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.002	0.002	0.002	0.001	0.002	0.002	0.002	0.001
2,000	0.004	0.003	0.005	0.002	0.004	0.005	0.004	0.002
3,000	0.005	0.005	0.007	0.004	0.006	0.007	0.005	0.002
4,000	0.008	0.007	0.009	0.006	0.008	0.009	0.008	0.006
5,000	0.009	0.009	0.011	0.007	0.010	0.011	0.009	0.007
6,000	0.012	0.011	0.013	0.010	0.012	0.013	0.012	0.010
7,000	0.015	0.014	0.016	0.012	0.014	0.016	0.014	0.012
8,000	0.018	0.018	0.018	0.016	0.017	0.018	0.017	0.016
9,000	0.031	0.031	0.029	0.027	0.021	0.031	0.028	0.021
10,000	0.054	0.070	0.050	0.055	0.038	0.070	0.053	0.038
11,000					0.074			
Pressure at Failure (psi)	10,900	10,680	10,700	10,450	11,300	11,300	10,806	10,450

Table G-26. Test Data on 1-Inch-Diameter, 120° Windows With t/D Ratio of 0.5, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	126	127	128	129	130			
Thickness, t (in.)	0.490	0.490	0.483	0.493	0.493	0.493	0.490	0.483
Temperature (°F)	67.5	68.0	69.0	67.5	66.5	69.0	67.7	66.5
Pressurization Rate (psi/min)	666	665	669	657	671	671	666	657
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.002	0.001	0.001	0.000	0.001	0.002	0.001	0.000
2,000	0.005	0.002	0.003	0.001	0.002	0.005	0.003	0.001
3,000	0.005	0.003	0.004	0.003	0.004	0.005	0.004	0.003
4,000	0.006	0.005	0.005	0.004	0.005	0.006	0.005	0.004
5,000	0.008	0.006	0.007	0.005	0.006	0.008	0.006	0.005
6,000	0.009	0.008	0.008	0.007	0.008	0.009	0.008	0.007
7,000	0.010	0.009	0.010	0.008	0.009	0.010	0.009	0.008
8,000	0.011	0.011	0.012	0.009	0.010	0.012	0.011	0.009
9,000	0.013	0.012	0.013	0.010	0.011	0.013	0.012	0.010
10,000	0.014	0.014	0.014	0.012	0.013	0.014	0.013	0.012
11,000	0.016	0.015	0.015	0.018	0.016	0.018	0.016	0.015
12,000	0.017	0.017	0.017	0.020	0.017	0.020	0.018	0.017
13,000	0.019	0.018	0.019	0.022	0.020	0.022	0.020	0.018
14,000	0.022	0.045	0.021	0.032	0.025	0.045	0.029	0.021
15,000	0.025	0.048	0.025	0.035	0.031	0.048	0.033	0.025
16,000	0.030	0.052	0.034	0.048	0.039	0.052	0.041	0.030
17,000	0.065	0.070	0.045	0.052	0.050	0.070	0.056	0.045
18,000	0.142	0.100	0.060	0.080	0.066	0.142	0.090	0.060
19,000			0.148	0.200	0.130	0.200	0.159	0.130
Pressure at Failure (psi)	18,400	18,700	19,300	19,300	19,300	19,300	19,000	18,400

Table G-27. Test Data on 1-Inch-Diameter, 120° Windows With t/D Ratio of 0.625, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	131	132	133	134	135			
Thickness, t (in.)	0.607	0.602	0.583	0.600	0.583	0.607	0.595	0.583
Temperature (°F)	63.5	65.5	67.0	67.5	67.5	67.5	66.2	63.5
Pressurization Rate (psi/min)	732	643	661	603	646	732	657	603
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.002	0.000	0.003	0.001	0.001	0.003	0.001	0.000
2,000	0.004	0.001	0.005	0.002	0.003	0.005	0.003	0.001
3,000	0.005	0.002	0.007	0.003	0.004	0.007	0.004	0.002
4,000	0.007	0.003	0.009	0.004	0.005	0.009	0.006	0.003
5,000	0.008	0.004	0.010	0.005	0.006	0.010	0.007	0.004
6,000	0.009	0.005	0.011	0.006	0.007	0.011	0.008	0.005
7,000	0.010	0.005	0.012	0.007	0.009	0.012	0.009	0.005
8,000	0.011	0.007	0.013	0.007	0.010	0.013	0.010	0.007
9,000	0.012	0.008	0.015	0.008	0.011	0.015	0.011	0.008
10,000	0.014	0.009	0.015	0.009	0.019	0.019	0.013	0.009
11,000	0.015	0.010	0.017	0.010	0.020	0.020	0.014	0.010
12,000	0.016	0.011	0.018	0.011	0.021	0.021	0.015	0.011
13,000	0.018	0.012	0.020	0.012	0.023	0.023	0.017	0.012
14,000	0.040	0.013	0.021	0.014	0.024	0.040	0.022	0.013
15,000	0.041	0.041	0.022	0.015	0.025	0.041	0.029	0.015
16,000	0.042	0.041	0.024	0.017	0.027	0.042	0.030	0.017
17,000	0.044	0.043	0.025	0.018	0.043	0.044	0.035	0.018
18,000	0.045	0.044	0.027	0.037	0.045	0.045	0.040	0.027
19,000	0.047	0.046	0.029	0.037	0.047	0.047	0.041	0.029
20,000	0.049	0.048	0.031	0.039	0.049	0.049	0.043	0.031
21,000	0.075	0.050	0.051	0.040	0.067	0.075	0.057	0.040
22,000	0.079	0.076	0.054	0.054	0.070	0.079	0.067	0.054
23,000	0.080	0.078	0.057	0.055	0.094	0.094	0.073	0.055
24,000	0.084	0.081	0.073	0.077	0.098	0.098	0.083	0.073
25,000	0.109	0.085	0.093	0.080	0.116	0.116	0.097	0.080
26,000	0.119	0.110	0.204	0.195	0.199	0.204	0.165	0.110
27,000	0.170	0.190				0.190	0.180	0.170
Pressure at Failure (psi)	27,900	27,700	26,300	26,500	26,700	27,900	27,020	26,300

Table G-28. Test Data on 1-Inch-Diameter, 150° Windows With t/D Ratio of 0.125, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	136	137	138	139	140			
Thickness, t (in.)	0.125	0.127	0.126	0.131	0.123	0.131	0.126	0.123
Temperature (°F)	65.5	61.9	66.5	67.1	69.1	69.1	66.0	61.9
Pressurization Rate (psi/min)	440	237	500	464	268	500	382	237
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
—	←(All failed at pressures below 1,000 psi)→							
Pressure at Failure (psi)	550	575	600	650	525	650	580	525

Table G-29. Test Data on 1-Inch-Diameter, 150° Windows With t/D Ratio of 0.25, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	141	142	143	144	145			
Thickness, t (in.)	0.245	0.240	0.244	0.248	0.249	0.249	0.245	0.240
Temperature (°F)	68.1	68.4	69.1	69.0	68.1	69.1	68.5	68.1
Pressurization Rate (psi/min)	672	664	667	635	618	672	651	618
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.003	0.004	0.002	0.002	0.003	0.004	0.003	0.002
2,000	0.005	0.007	0.005	0.004	0.005	0.007	0.005	0.004
3,000	0.007	0.013	0.012	0.011	0.009	0.013	0.010	0.007
4,000	0.011	0.047	0.023			0.047	0.027	0.011
5,000	0.024							
Pressure at Failure (psi)	5,450	4,550	4,750	3,950	3,800	5,450	4,500	3,800

Table G-30. Test Data on 1-Inch-Diameter, 150° Windows With t/D Ratio of 0.375, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	146	147	148	149	150			
Thickness, t (in.)	0.360	0.375	0.343	0.357	0.335	0.375	0.354	0.335
Temperature (°F)	66.5	67.9	67.5	67.6	67.6	67.9	67.4	66.5
Pressurization Rate (psi/min)	663	652	678	669	667	678	666	652
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.001	0.002	0.002	0.001	0.001	0.002	0.001	0.001
2,000	0.002	0.004	0.004	0.003	0.002	0.004	0.003	0.002
3,000	0.003	0.006	0.006	0.004	0.004	0.006	0.005	0.003
4,000	0.005	0.007	0.007	0.007	0.007	0.007	0.007	0.005
5,000	0.006	0.009	0.009	0.009	0.009	0.009	0.008	0.006
6,000	0.008	0.010	0.011	0.010	0.012	0.012	0.010	0.008
7,000	0.011	0.012	0.013	0.013	0.016	0.016	0.013	0.011
8,000	0.013	0.013	0.018	0.015	0.019	0.019	0.016	0.013
9,000	0.015	0.029	0.034	0.018	0.027	0.034	0.025	0.015
10,000	0.018	0.031	0.049	0.024	0.059	0.059	0.036	0.018
11,000	0.032	0.040		0.038		0.040	0.037	0.032
12,000		0.061				0.061	0.061	0.061
Pressure at Failure (psi)	11,500	12,525	10,550	11,300	10,100	12,525	11,195	10,100

Table G-31. Test Data on 1-Inch-Diameter, 150° Windows With t/D Ratio of 0.5, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	151	152	153	154	155			
Thickness, t (in.)	0.465	0.461	0.468	0.467	0.467	0.468	0.466	0.461
Temperature (°F)	67.9	67.2	68.2	68.1	67.4	68.2	67.8	67.2
Pressurization Rate (psi/min)	667	665	659	663	669	669	665	659
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.001	0.001	0.001	0.001	0.002	0.002	0.001	0.001
2,000	0.002	0.003	0.002	0.003	0.003	0.003	0.003	0.002
3,000	0.003	0.004	0.003	0.004	0.004	0.004	0.004	0.003
4,000	0.004	0.005	0.005	0.005	0.006	0.006	0.005	0.004
5,000	0.005	0.006	0.006	0.007	0.007	0.007	0.006	0.005
6,000	0.007	0.007	0.006	0.008	0.008	0.008	0.007	0.006
7,000	0.008	0.008	0.008	0.010	0.009	0.010	0.009	0.008
8,000	0.009	0.009	0.011	0.011	0.010	0.011	0.010	0.009
9,000	0.010	0.010	0.013	0.013	0.011	0.013	0.011	0.010
10,000	0.011	0.011	0.018	0.015	0.013	0.018	0.014	0.011
11,000	0.012	0.013	0.021	0.016	0.014	0.021	0.015	0.012
12,000	0.015	0.015	0.027	0.019	0.016	0.027	0.018	0.015
13,000	0.017	0.017	0.031	0.040	0.018	0.031	0.025	0.017
14,000	0.027	0.020	0.042	0.043	0.021	0.043	0.031	0.020
15,000	0.030	0.022	0.048	0.045	0.023	0.048	0.034	0.022
16,000	0.046	0.026	0.064	0.065	0.026	0.065	0.045	0.026
17,000	0.070	0.034	0.095	0.091	0.030	0.095	0.064	0.030
18,000	0.150				0.056	0.150	0.103	0.056
Pressure at Failure (psi)	18,100	17,600	17,550	17,650	18,150	18,150	17,810	17,550

Table G-32. Test Data on 1-Inch-Diameter, 150° Windows With t/D Ratio of 0.5, in DOL Type I Flange: Sample Group Size Validation Tests

	Specimen Number					Maximum Value	Average Value	Minimum Value
	156	157	158	159	160			
Thickness, t (in.)	0.498	0.485	0.498	0.504	0.500	0.504	0.497	0.485
Temperature (°F)	65.8	69.1	67.9	66.1	68.5	69.1	67.5	65.8
Pressurization Rate (psi/min)	662	661	642	672	656	672	659	642
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.003	0.001	0.003	0.002	0.002	0.003	0.002	0.001
2,000	0.004	0.002	0.004	0.003	0.0035	0.004	0.003	0.002
3,000	0.005	0.003	0.006	0.004	0.005	0.006	0.0045	0.003
4,000	0.006	0.0035	0.007	0.005	0.006	0.007	0.005	0.0035
5,000	0.007	0.004	0.008	0.006	0.007	0.008	0.006	0.004
6,000	0.008	0.011	0.009	0.007	0.008	0.011	0.009	0.007
7,000	0.009	0.012	0.010	0.008	0.009	0.012	0.010	0.008
8,000	0.0095	0.018	0.012	0.0085	0.012	0.018	0.012	0.0085
9,000	0.021	0.020	0.013	0.009	0.013	0.021	0.015	0.009
10,000	0.022	0.022	0.014	0.010	0.022	0.022	0.018	0.010
11,000	0.023	0.028	0.016	0.011	0.024	0.028	0.020	0.011
12,000	0.024	0.035	0.016	0.012	0.025	0.035	0.022	0.012
13,000	0.035	0.036	0.018	0.013	0.032	0.036	0.027	0.013
14,000	0.036	0.043	0.019	0.015	0.038	0.043	0.030	0.015
15,000	0.037	0.049	0.021	0.016	0.039	0.049	0.032	0.016
16,000	0.045	0.065	0.058	0.018	0.043	0.065	0.046	0.018
17,000	0.047	0.066	0.061	0.020	0.050	0.066	0.049	0.020
18,000	0.056	0.082	0.064	0.022	0.056	0.082	0.056	0.022
19,000	0.064	0.125	0.089	0.025	0.066	0.125	0.074	0.025
20,000	0.092		0.150	0.034	0.105	0.150	0.095	0.034
21,000	0.153			0.150		0.153	0.1515	0.150
Pressure at Failure (psi)	21,200	19,550	20,200	21,000	20,750	21,200	20,540	19,550

Table G-33. Test Data on 1-Inch-Diameter, 150° Windows With t/D Ratio of 0.625, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	161	162	163	164	165			
Thickness, t (in.)	0.602	0.602	0.606	0.596	0.589	0.606	0.599	0.589
Temperature (°F)	67.7	69.0	66.0	70.4	68.4	70.4	68.3	66.0
Pressurization Rate (psi/min)	664	662	504	653	603	664	617	504
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.002	0.005	0.004	0.002	0.003	0.005	0.0032	0.002
2,000	0.008	0.006	0.005	0.004	0.004	0.008	0.005	0.004
3,000	0.009	0.007	0.006	0.006	0.005	0.009	0.0066	0.005
4,000	0.010	0.008	0.007	0.007	0.006	0.010	0.0076	0.006
5,000	0.011	0.009	0.0085	0.008	0.007	0.011	0.0087	0.007
6,000	0.0115	0.010	0.0095	0.010	0.008	0.0115	0.0098	0.008
7,000	0.012	0.011	0.010	0.011	0.010	0.012	0.0108	0.010
8,000	0.013	0.012	0.012	0.012	0.011	0.013	0.012	0.011
9,000	0.014	0.013	0.013	0.013	0.011	0.014	0.013	0.011
10,000	0.014	0.014	0.0145	0.015	0.012	0.015	0.014	0.012
11,000	0.015	0.015	0.015	0.020	0.013	0.020	0.0156	0.013
12,000	0.016	0.016	0.0165	0.024	0.014	0.024	0.0173	0.014
13,000	0.017	0.017	0.018	0.026	0.015	0.026	0.0186	0.015
14,000	0.0175	0.018	0.0195	0.031	0.016	0.031	0.0204	0.016
15,000	0.018	0.020	0.0205	0.035	0.017	0.035	0.022	0.017
16,000	0.019	0.021	0.022	0.039	0.025	0.039	0.025	0.019
17,000	0.020	0.022	0.024	0.043	0.025	0.043	0.027	0.020
18,000	0.022	0.024	0.025	0.049	0.026	0.049	0.029	0.022
19,000	0.0245	0.025	0.027	0.055	0.032	0.055	0.035	0.0245
20,000	0.027	0.028	0.029	0.062	0.033	0.062	0.036	0.027
21,000	0.030	0.029	0.031	0.072	0.037	0.072	0.040	0.029
22,000	0.032	0.032	0.051	0.081	0.048	0.081	0.049	0.032
23,000	0.035	0.035	0.053	0.097	0.054	0.097	0.055	0.035
24,000	0.038	0.076	0.068	0.145	0.077	0.145	0.081	0.038
25,000	0.042	0.085	0.120			0.120	0.082	0.042
26,000	0.066	0.125	0.280			0.280	0.157	0.066
27,000	0.110					0.110	0.110	0.110
Pressure at Failure (psi)	27,500	26,850	26,150	24,800	24,700	27,500	26,000	24,700

Table G-34. Test Data on 2-Inch-Diameter, 30° Windows With t/D Ratio of 0.125, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	166	167	168	169	170			
Thickness, t (in.)	0.244	0.254	0.257	0.265	0.264	0.265	0.257	0.244
Temperature (°F)	70.8	70.1	69.7	69.4	69.8	70.8	69.9	69.4
Pressurization Rate (psi/min)	697	570	687	517	662	697	627	517
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
250	0.007	0.005	0.007	0.007	0.007	0.007	0.007	0.005
500	0.018	0.013	0.015	0.014	0.014	0.018	0.015	0.013
750	0.050	0.040	0.028	0.025	0.026	0.050	0.034	0.025
Pressure at Failure (psi)	850	850	900	900	900	900	880	850

Table G-35. Test Data on 2-Inch-Diameter, 30° Windows With t/D Ratio of 0.25, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	171	172	173	174	175			
Thickness, t (in.)	0.490	0.485	0.490	0.485	0.485	0.490	0.487	0.485
Temperature (°F)	70.0	69.1	69.2	70.5	69.5	70.5	69.7	69.1
Pressurization Rate (psi/min)	658	604	659	679	655	679	651	604
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
250	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
500	0.005		0.005	0.005	0.005	0.005	0.005	0.005
750	0.008		0.007	0.009	0.007	0.009	0.008	0.007
1,000	0.010	0.009	0.009	0.012	0.009	0.012	0.010	0.009
1,250	0.013	0.012	0.011	0.015	0.012	0.015	0.013	0.011
1,500	0.017	0.015	0.015	0.018	0.016	0.018	0.016	0.015
1,750	0.020	0.018	0.018	0.022	0.019	0.022	0.019	0.018
2,000	0.024	0.021	0.021	0.028	0.023	0.028	0.023	0.021
2,250	0.028	0.025	0.032	0.033	0.028	0.033	0.029	0.025
2,500	0.032	0.031	0.045	0.040	0.033	0.045	0.036	0.031
2,750	0.060	0.070	0.070	0.046	0.039	0.070	0.057	0.039
3,000	0.110	0.110	0.110	0.070	0.075	0.110	0.095	0.070
Pressure at Failure (psi)	3,225	3,175	3,250	3,250	3,275	3,275	3,235	3,175

Table G-36. Test Data on 2-Inch-Diameter, 30° Windows With t/D Ratio of 0.5, in DOL Type I Flange: t/D Ratio Validation Tests

	Specimen Number					Maximum Value	Average Value	Minimum Value
	176	177	178	179	180			
Thickness, t (in.)	0.957	0.954	0.954	0.971	0.965	0.971	0.960	0.954
Temperature (°F)	64.5	67	64.5	62.8	68	68	65.4	62.8
Pressurization Rate (psi/min)	435	657	663	613	657			
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.005	0.011	0.008	0.007	0.011	0.011	0.008	0.005
2,000	0.013	0.028	0.019	0.012	0.029	0.029	0.020	0.012
3,000	0.021	0.048	0.037	0.025	0.050	0.050	0.036	0.021
4,000	0.050	0.076	0.061	0.048	0.075	0.076	0.062	0.048
5,000	0.078	0.104	0.091	0.074	0.105	0.105	0.090	0.074
6,000	0.118	0.151	0.128	0.110	0.154	0.154	0.132	0.110
7,000	0.200	0.249	0.207	0.189	0.250	0.250	0.219	0.189
8,000	0.450							
Pressure at Failure (psi)	8,100	7,400	7,450	7,900	7,300	8,100	7,630	7,300

Table G-37. Test Data on 2-Inch-Diameter, 30° Windows With t/D Ratio of 1.0, in DOL Type II Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	181	182	183	184	185			
Thickness, t (in.)	2.008	0.981	1.981	1.993	2.001	2.008	1.993	1.981
Temperature (°F)	67	70	71	66	65	71	67.8	65
Pressurization Rate (psi/min)	658	655	666	655	661	666	659	655
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.004	0.005	0.003	0.004	0.004	0.005	0.004	0.003
2,000	0.008	0.015	0.007	0.018	0.024	0.024	0.0144	0.007
3,000	0.013	0.027	0.042	0.046	0.034	0.046	0.0324	0.013
4,000	0.021	0.039	0.045	0.041	0.044	0.045	0.0380	0.021
5,000	0.034	0.051	0.073	0.057	0.061	0.073	0.0552	0.034
6,000	0.045	0.065	0.076	0.072	0.073	0.076	0.0662	0.045
7,000	0.059	0.082	0.099	0.088	0.092	0.099	0.0840	0.059
8,000	0.074	0.099	0.104	0.103	0.109	0.109	0.0978	0.074
9,000	0.093	0.117	0.110	0.118	0.124	0.118	0.1124	0.093
10,000	0.110	0.138	0.142	0.139	0.148	0.148	0.1354	0.110
11,000	0.133	0.165	0.156	0.168	0.171	0.171	0.1586	0.133
12,000	0.157	0.196	0.198	0.201	0.202	0.202	0.1908	0.157
13,000	0.190	0.240	0.234	0.228	0.240	0.240	0.2264	0.190
14,000	0.225	0.290	0.288	0.259	0.285	0.290	0.2694	0.225
15,000	0.267	0.335	0.334	0.299	0.325	0.335	0.3120	0.267
16,000	0.310	0.382	0.382	0.340	0.371	0.382	0.3570	0.310
17,000	0.349	0.429	0.442	0.379	0.425	0.442	0.4048	0.349
18,000	0.395	0.485	0.543	0.419	0.484	0.543	0.4652	0.395
19,000	0.440	0.570	0.675		0.581	0.675	0.5665	0.440
20,000	0.508				0.780	0.780	0.6440	0.508
Pressure at Failure (psi)	20,800	20,400	19,800	20,500	20,500	20,800	20,400	19,800

Table G-38. Test Data on 4.5-Inch-Diameter, 60° Windows With t/D Ratio of 0.125, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	186	187	188	189	190			
Thickness, t (in.)	0.555	0.550	0.555	0.550	0.555	0.555	0.553	0.550
Temperature (°F)	67	67	67	67	67.5	67.5	67.1	67
Pressurization Rate (psi/min)	655	621	578	708	533	708	619	533
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
250	0.010	0.011	0.018	0.015	0.032	0.032	0.017	0.010
500	0.044	0.042	0.055	0.050	0.078	0.078	0.054	0.042
750	0.088	0.090	0.095	0.090		0.095	0.090	0.088
Pressure at Failure (psi)	950	925	1,000	850	650	1,000	875	650

Table G-39. Test Data on 4.5-Inch-Diameter, 60° Windows With t/D Ratio of 0.25, in DOL Type I Flange

	Specimen Number					Maximum Value	Average Value	Minimum Value
	191	192	193	194	195			
Thickness, t (in.)	1.114	1.119	1.134	1.135	1.159	1.159	1.132	1.114
Temperature (°F)	67.1	67.0	65.5	68.8	70.7	70.7	67.8	65.5
Pressurization Rate (psi/min)	609	651	639	633	637	651	634	609
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.022	0.013	0.015	0.014	0.014	0.022	0.016	0.013
2,000	0.052	0.044	0.042	0.040	0.044	0.052	0.044	0.040
3,000	0.089	0.079	0.078	0.072	0.080	0.089	0,080	0.072
4,000	0.136	0.130	0.128	0.121	0.132	0.136	0.129	0.121
5,000	0.208	0.212	0.201	0.195	0.197	0.212	0.203	0.195
Pressure at Failure (psi)	5,600	5,850	5,850	5,900	5,750	5,900	5,790	5,600

Table G-40. Test Data on 4.5-Inch-Diameter, 60° Windows With t/D Ratio of 0.5, in DOL Type I Flange: t/D Ratio Validation Tests

	Specimen Number					Maximum Value	Average Value	Minimum Value
	196	197	198	199	200			
Thickness, t (in.)	2.270	2.250	2.240	2.348	2.250	2.348	2.272	2.240
Temperature (°F)	62.5	67.5	64	69.5	63.5	69.5	65.4	62.5
Pressurization Rate (psi/min)	456	211	325	628	625	211	628	449
Pressure (psi)	Axial Displacement of Center Point on Window Low-Pressure Face (in.)							
1,000	0.006	0.008	0.008	0.011	0.004	0.011	0.007	0.004
2,000	0.014	0.019	0.023	0.017	0.029	0.029	0.020	0.014
3,000	0.020	0.036	0.038	0.026	0.034	0.038	0.031	0.020
4,000	0.032	0.053	0.055	0.045	0.055	0.055	0.048	0.032
5,000	0.048	0.070	0.071	0.062	0.065	0.071	0.063	0.048
6,000	0.066	0.089	0.089	0.081	0.091	0.091	0.083	0.066
7,000	0.086	0.112	0.108	0.103	0.122	0.122	0.106	0.086
8,000	0.108	0.138	0.129	0.127	0.128	0.138	0.126	0.108
9,000	0.137	0.168	0.155	0.155	0.160	0.168	0.155	0.137
10,000	0.175	0.224	0.188	0.181	0.188	0.224	0.191	0.175
11,000	0.211	0.303	0.230	0.213	0.234	0.303	0.238	0.211
12,000	0.241	0.412	0.294	0.274	0.282	0.412	0.301	0.241
13,000	0.282		0.436	0.337	0.363	0.436	0.354	0.282
14,000	0.341		0.700	0.438	0.490	0.700	0.492	0.341
15,000	0.441							
16,000	0.730							
Pressure at Failure (psi)	16,000	12,500	14,100	14,650	14,650	16,000	14,380	12,500

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U. S. Naval Civil Engineering Laboratory
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TR-512 100 p. illus Jan 1967 Unclassified

1. Undersea vessels 2. Conical acrylic windows I. Y-F015-01-07-001

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Acrylic windows, in the form of truncated cones with included angles of 30°, 60°, 90°, 120°, and 150°, were tested to destruction at ambient room temperature by applying hydrostatic pressure to the base of the truncated cone at a continuous rate of 650 psi/min. The pressure at which the windows failed and the magnitude of displacement through the window mounting at different pressure levels were recorded. The ultimate strength of the conical windows (denoted by the critical pressure at which actual failure occurred) was found to be related both to thickness and included conical angle.

Graphs are presented defining the relationships of critical pressure versus thickness-to-diameter ratio, and pressure versus magnitude of displacement for the windows.

Nondimensional scaling factors for critical pressure and displacement applicable to large-diameter windows are discussed and presented in graphic form.

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13. ABSTRACT

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